Modeling Spatial and Temporal Changes of Ponderosa Pine Forests in Northern Arizona since Euro-American Settlement

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Abstract

Modeling Spatial and Temporal Changes of Ponderosa Pine Forests in Northern Arizona since Euro-American Settlement

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This dissertation research was conducted on 13 historically stem-mapped, permanent plots, representing the pure ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum*) and the ponderosa pine-Gambel oak (*Quercus gambelii* Nutt.) in north-central Arizona. These plots were established in 1909 and 1913, respectively, sampled until the 1950s, and resampled between 2002 and 2006. For this research, I developed structural reference conditions and examined the long-term vegetation dynamics, focusing on changes in tree size structure, tree spatial patterns and contemporary pine recruitment.

I used spatial analyses to examine the short- and long-term changes exhibited at one site, a 2.59-ha historically stem-mapped ponderosa pine plot that was initially harvested in the late 1800s, and showed that tree spatial and temporal recruitment patterns were not random. The harvest also changed spatial patterns by homogenizing tree size within forest patches. Post-harvest recruitment patterns suggest that pine seedlings initially established in natural grass openings and then proceeded to colonize stump patches created by harvesting until tree growing space was fully occupied in the 1940s.

I used six of the historically stem-mapped, permanent plots, containing detailed information on stumps, snags, and logs, to develop a reconstruction model and provide structural reference conditions for ponderosa pine forests of north-central Arizona. Furthermore, I proposed a new method for delineating groups of trees or patches, and quantified tree and patch spatial pattern for the above reconstructed reference conditions. The method I proposed standardizes between- and within-patch analyses and, when coupled with stand-level analysis of spatial patterns, provides a more complete picture of forest structure prior to Euro-American settlement.

Reference conditions for these plots in 1873-1874 included the following reconstructed stand attributes: tree densities ranged from 45 to 127 trees ha^{-1}, quadratic mean diameter ranged from 41.5 to 51.3 cm, and basal area ranged from 9.2 to 18.0 m^2 ha^{-1}. The reconstructed diameter distributions (for live ponderosa pine trees $\geq$9.14 cm; diameter at breast height (1.37 m); DBH) prior to fire exclusion varied in shape, but generally displayed an irregular, uneven-aged size distribution with one or two dominant size cohorts. Presettlement patch densities ranged from 10 to 27 patches ha^{-1}, which accounted for 62% to 75% of the stand basal area (m^2 ha^{-1}).

Lastly, I analyzed forest structural characteristics and tree recruitment patterns on a ponderosa pine-Gambel oak site that received harvests from three different systems in the early 1900s (Seed Tree, Group Selection, and Light Selection). Using Ripley's K(t) univariate and $K_{12}(t)$ bivariate analysis, I examined the short- and long-term consequences of harvest and livestock grazing, as well as provided insight into stand dynamics for trees $\geq$9.14 cm. Intensive harvests (i.e., Seed Tree) effectively converted the spatial patterns to random, while the less intensive (i.e., Group Selection and Light

Selection) harvesting systems had varying effects, but generally accentuated the patchiness of pre-existing spatial patterns.

The long-term impact of timber harvesting and livestock grazing, which occurred over 90 years ago, has complex and lasting effects that are reflected in the contemporary ponderosa pine forest structure of north-central Arizona. Quantifying the influence of land-use legacies on forest structure provides insight into stand dynamics and development, which have been shown to affect wildlife habitat, understory production, and fire behavior; therefore, it should be explicitly incorporated into management and restoration activities.

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"Eighty-five percent of the variability in y can be explained by the variability in x, the remaining fifteen percent is attributed to magic."

Anonymous

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I thank Susan Olberding, who provided access to historical data, which are housed in the Fort Valley Experimental Station Archives (Flagstaff, AZ). In addition, I thank the early researchers of Fort Valley. Herman Krauch and Clarence Korstian established the plots, on which Chapter 5 is based, and Gus Pearson and Theodore Woolsey Jr. established the Woolsey plots, on which all of my dissertation work is based. Without their foresight, none of my research would have possible.

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Preface

This dissertation has been prepared in journal format, resulting in some redundancy among chapters. Chapter 2, "Short- and long-term effects of selective harvesting on spatial pattern and stand development in a ponderosa pine forest", will be submitted to *Journal of Vegetation Science*. Chapter 3, "Using historically stem-mapped permanent plots to quantify reference conditions in ponderosa pine forests of north-central Arizona", will be submitted to *Forest Science*. Chapter 4, "A new method for determining spatial reference conditions in ponderosa pine forests of north-central Arizona", will be submitted to *Ecological Applications*. Chapter 5, "Land-use legacies in a southwestern ponderosa pine-Gambel oak forest: A case study" will be submitted to *Forest Ecology and Management*.

Chapter 1

Introduction

The initial settlement of the northern Arizona by early Euro-Americans markedly changed forest structure through intensive logging, livestock grazing and fire suppression, as well as indirectly through fire exclusion (Cooper 1960, Covington and Moore 1994, Fulé et al. 1997, Allen et al. 2002, Moore et al. 2004, Cocke et al. 2005). These legacies of past land-use practices, or land-use legacies (a.k.a. site history or disturbance history), likely influenced forest structure and function for decades or even centuries (Foster et al. 2003). Scientists and managers recognize the importance of land-use legacies and realize that only when we quantify the impact of these past activities, can we use this information to model contemporary or future conditions.

An understanding of disturbance history and vegetation change provides a context for ecological studies (Christensen 1989, Pickett et al. 1997), a basis for natural resource management and planning (Moore et al. 1999, Swetnam et al. 1999, Egan and Howell 2001), and is essential in restoration modeling (e.g., Covington et al. 2001). Contemporary management practices in southwestern ponderosa pine ecosystems must consider the historical context under which current forest structure developed and changed.

Long-term studies are critical to several areas of forest research such as vegetation dynamics, plant spatial patterns, and silvicultural and forest restoration prescriptions

(Sheppard and Edminster 1997, Pickett et al. 2001). Remeasurements of plots established in long-term studies have revealed large changes in tree growth due to reductions in stand density (Schubert 1971, Ronco et al. 1985), herbaceous production following restoration treatments (Laughlin et al. 2006), and in forest structure and composition (Moore et al. 2004). Permanent plots provide direct insights into forest development, which complement reconstructive and space-for-time techniques. Whereas chronosequence studies may confound site differences and temporal changes (Bakker et al. 1996), using long-term permanent plots ensures that forest processes are examined at the same spatial and temporal scales.

Similarly, the analysis of changes in tree spatial patterns enables researchers and managers to relate observed structural characteristics to processes such as regeneration, competition, and mortality (Dale 1999, Youngblood et al. 2004). Thus, spatial pattern analyses can further increase understanding of plant community dynamics (Levin 1992, Dale 1999, Fortin and Dale 2005) and the consequences of land-use legacies on community structure (Foster et al. 2003). This is particularly true in southwestern ponderosa pine forests where restoration efforts are in progress, but tree spatial data deemed essential for understanding heterogeneity in contemporary and historical stand structures (Youngblood et al. 2004, Boyden et al. 2005) are inadequate or lacking.

These restoration projects assume that managing for forest structure similar to that of reference conditions will maintain important ecosystem structure and function, which in turn reduce the risk of wildfires and insect or disease epidemics (Swanson et al. 1994, Landres et al. 1999, Moore et al. 1999, Allen et al. 2002). In many cases where contemporary forests have been degraded and conditions are outside their range of

natural variability, reference conditions also serve to guide silvicultural treatments (Morgan et al. 1994, Fulé et al. 1997, Moore et al. 1999, Swetnam et al. 1999). Thus, identification of suitable reference conditions is an essential step in the ecosystem restoration planning process (Kaufmann et al. 1994, Arno et al. 1995, Fulé et al. 1997, Covington et al. 1997).

Dissertation Structure

This dissertation is based on data obtained from thirteen permanent plots established in either 1909 or 1913. These plots were established after several decades of intense livestock grazing and fire exclusion, but before the strong pulse of ponderosa pine regeneration that occurred throughout much of the ponderosa pine forests of northern Arizona (Pearson 1950, Savage et al. 1996). Other studies based on these sites include Krauch (1933, 1934, 1937), Lexen (1939), Pearson (1923, 1944, 1950) and Moore et al. (2004).

In Chapters 2 and 5, I examined the effects of three harvesting systems and livestock grazing on tree spatial patterns and contemporary pine recruitment. For these chapters, I focused on changes between unharvested and harvested conditions at plot establishment (1909 or 1913) and contemporary conditions (2002-2006). While unharvested conditions at plot establishment are obviously not exactly the same as 'reference' (Moore et al. 1999), the changes that have occurred since then provide the historical context under which contemporary forest structure developed and changed over the recent century. Specific research questions common to both studies were: (1) How might forest structure have looked in the absence of harvesting around the time of plot establishment (1909-1913)? (2) How did each harvesting affect stand characteristics and

spatial patterns over the short-term (immediately following initial harvests)? (3) How did stand characteristics and spatial patterns change over the long-term (as observed in 2002-2006)? (4) How did the stand structural patterns resulting from harvesting and livestock grazing influence the recruitment of subsequent ponderosa pine cohorts?

Then, in Chapters 3 and 4, the conditions I examine do represent 'reference', as they are reconstructed prior to the activities associated with Euro-American settlement for this area (intensive logging, livestock grazing, fire exclusion and fire suppression). This information quantifies the spatial and structural characteristics of the presettlement forest, which may, in turn, be used to validate commonly used dendrochronological reconstruction techniques, serve as baseline for comparisons with contemporary conditions, and provide guidance in determining forest structural restoration objectives. Specific research objectives for these studies were: (1) To determine presettlement forest reference conditions (including both live and dead trees) for ponderosa pine forests of north-central Arizona, (2) to further quantify structure by investigating the spatial pattern of presettlement trees (3) to propose a new method for delineating patches (4) to compare these reconstructions of structure to other similar studies and (5) to suggest how can land managers might incorporate this information into their current and future land management goals.

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Chapter 2

Short- and Long-Term Effects of Selective Harvesting on Spatial Pattern and Stand Development in a Ponderosa Pine Forest

Abstract

Analysis of changes in spatial pattern enables researchers and managers to relate observed structural characteristics to processes such as regeneration, competition, and mortality. Thus, spatial pattern analyses can increase understanding of forest dynamics and the consequences of management activities (i.e., harvesting fire exclusion, grazing) on forest structure. I describe the spatial patterns of on a 2.59-ha historically stem-mapped ponderosa pine site that was selectively harvested in 1894 for the following three stand structural scenarios: 1909 harvested (actual) and unharvested (modeled) and 2002 (actual) conditions. For 1909 scenarios, I used historical stem-maps, ledger data, contemporary data, and dendrochronological techniques to reconstruct stand structure (size, age, density). I used Clark and Evans' R, Ripley's K(t) univariate analysis, and correlogram analysis to assess changes in spatial pattern in each scenario. I then used Ripley's $K_{12}(t)$ bivariate analysis, semivariograms, and kriging to examine spatial and temporal tree recruitment patterns as observed in the contemporary (2002) stand for trees $\geq$9.14 cm diameter at breast height (1.37 m). The 1894 harvest exaggerated the spatial patchiness of the stand in 1909 at the patch scale (0.02 ha) and the extent (2.59 ha). The 1894 selective harvest also changed spatial patterns by homogenizing tree size variability

within patches. By 2002, the stand was aggregated at all scales and was one large patch of predominately small trees. Post-harvest recruitment patterns were not spatially random; pine seedlings initially established in natural grass openings and then proceeded to fill-in stump patches created by harvesting. Spatial pattern is an important component of ponderosa pine forests, affecting wildlife habitat, understory production, fire behavior, and other factors, and therefore should be explicitly quantified and incorporated into management and restoration activities.

Introduction

Much has been written about the dramatic structural and functional changes that ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum*) forests of the Southwest have undergone since Euro-American settlement (Covington & Moore 1994; Fulé et al. 1997; Allen et al. 2002; Moore et al. 2004). These studies focused primarily on temporal changes and stand-level attributes such as tree density, but did not attempt to provide quantitative data about spatial patterns. A review of the literature revealed three studies (Cooper 1960; White 1985; Biondi et al. 1994) where quantifying spatial patterns in southwestern ponderosa pine forests was the objective and three other studies in which ponderosa pine spatial patterns were examined in the Colorado Front Range (Mast & Veblen 1999; Boyden et al. 2005) and eastern Oregon and California (Youngblood et al. 2004). Analysis of changes in tree spatial patterns enables researchers and managers to relate observed structural characteristics to processes such as regeneration, competition, and mortality (Dale 1999; Youngblood et al. 2004). Thus, spatial pattern analyses can increase understanding of plant community dynamics (Levin 1992; Dale 1999; Fortin &

Dale 2005) and the consequences of past and present management activities (i.e., fire exclusion, grazing, thinning, etc.) on community structure (Foster et al. 2003). This is particularly true in southwestern ponderosa pine forests where restoration efforts are in progress; but tree spatial data deemed essential for understanding heterogeneity in contemporary and historical stand structures (Youngblood et al. 2004; Boyden et al. 2005) are inadequate or lacking.

Tree regeneration is a major, spatially-dependent factor in forest stand development. In the Southwest, ponderosa pine seedlings establish in groups, often near or under parent trees (Pearson 1923; White 1985). Ponderosa pine regeneration has been reported to be more abundant to the northeast of seed trees (Pearson 1942; Haase 1981), persists at higher densities on limestone- than basalt-derived soils (Heidmann et al. 1982; Goodwin 2004), is episodic in nature (Pearson 1950; Savage & Swetnam 1990; Savage et al. 1996; Mast et al. 1999; Allen et al. 2002; Bailey & Covington 2002; Brown & Wu 2005), and is limited by drought and competition with herbaceous vegetation (Pearson 1942; 1950; Schubert 1974; Kolb & Robberecht 1996). It is also generally accepted that postsettlement southwestern ponderosa pine succession follows a 'gap' model (Watt 1947; Stephens & Fry 2005), where even-aged patches of shade-intolerant seedlings originate in small forest openings (Cooper 1960; 1961; White 1985; Fulé et al. 2002). Although it is assumed that a similar pine regeneration establishment pattern occurred in presettlement times, prior to 1876 surface fires were frequent and would have acted as a thinning agent on the pine seedling patches, most likely resulting in uneven-aged patches (White 1985; Fulé et al. 2002; Stephens & Fry 2005). As a consequence of removing frequent surface fires and grass competition (primarily resulting from livestock

overgrazing) as regulatory factors, ponderosa pine forests of northern Arizona experienced a population explosion in the early 1900s, which has been studied extensively (Pearson 1950; Cooper 1960; Schubert 1974; White 1985; Covington & Moore 1994; Savage et al. 1996; Mast et al. 1999; Moore et al. 2004; Bakker 2005). Yet, the influence that early logging practices had on pine establishment patterns and the resulting stand development has not been studied. Understanding these historical legacies will add to the general understanding of how past management activities and disturbance events have influenced contemporary forest conditions, thus allowing managers to better understand the consequences of their decisions (Foster et al. 2003; Taylor 2004).

I used point pattern and geostatistical analyses to address the short- and long-term effects of early timber harvesting on the spatial patterns and dynamics of a historically (1909) stem-mapped ponderosa pine stand in north-central Arizona. I asked the following questions: (1) Were trees aggregated into groups, prior to selective harvesting in 1894, in a ponderosa pine stand in north-central Arizona? (2) Were tree sizes spatially autocorrelated and what insight does this information provide regarding patch characteristics? (3) How did selective harvesting in 1894 affect stand characteristics and spatial patterns over the short-term (as observed in 1909)? (4) How did stand characteristics and spatial patterns change over the long-term (as observed in 2002)? (5) How did the residual stand structural patterns influence the recruitment of subsequent ponderosa pine cohorts; and where did these cohorts establish? (6) Were ponderosa pine seedlings recruited in canopy gap openings and were these natural openings or those

created by harvesting? (7) Did recruitment occur all at once or in multiple, distinct cohorts?

Methods

Study Site

The study site is located 10 km NW of Flagstaff, Arizona on the Fort Valley Experimental Forest within the Coconino National Forest (35°15.94′ N, 111°44.99′ W). Ponderosa pine is the only tree species present on the site, and the understory vegetation is predominantly perennial bunchgrasses. The elevation is approximately 2240 m. Soils, derived from Tertiary basalt flows and cinders, are classified as a complex of fine, smectitic Typic Argiborolls and Mollic Eutroboralfs, primarily with clay loam and stony clay textures (Kerns et al. 2003). The site is in Terrestrial Ecosystem Unit 582, which is representative of just under 56,000 ha (7%) of the Coconino National Forest (Miller et al. 1995). Mean annual temperature is 7.5° C and mean annual precipitation 57 cm, following a monsoonal precipitation pattern with half of the precipitation as rain in July and August, and half as snow in the winter.

The site, known as COCS1A (2.59 ha, 160 x 160 m), was established in 1909 as part of a network of permanent plots used to quantify ponderosa pine growth at the tree and stand levels (Pearson 1923; 1933; Moore et al. 2004). Secondary objectives were to compare the effects of different harvesting and slash disposal practices on stand dynamics and to determine the effects of herbaceous competition, soil, and disturbance events (primarily timber harvesting, livestock grazing, fire, and pest outbreaks) on the natural regeneration of ponderosa pine (Woolsey 1911; 1912; Pearson 1923; 1933; Moore et al.

2004). COCS1A had been selectively harvested in 1894 by the Greenlaw Lumber Company, with the objective of retaining 8 to 10 mature seed trees (> 200 years old) per ha (Pearson 1923) to provide a source of regeneration (Nyland 1996). The plot was fenced to exclude cattle and sheep grazing in 1909.

All live trees with diameter at breast height (DBH; 1.37 meters above ground level) ≥9.14 cm (3.6 in) were measured and stem-mapped at plot establishment (Fig. 2.1). Tree condition, DBH, and other variables were recorded in a ledger that is currently housed in the Fort Valley Archives (Rocky Mountain Research Station, USDA Forest Service, Flagstaff, AZ). The residual tree density following the 1894 selective harvest was 52 trees per hectare (TPH). In 1941, the plot was thinned, removing 16 TPH (mean DBH: 48.7 cm, SD: 21.4 cm) and leaving a residual stand density of 401 TPH.

Data Collection

Historical and contemporary field methods are detailed by Moore et al. (2004), who also report on stand structure changes within a 1-ha subplot of this and other permanent plots throughout Arizona and New Mexico. For this study, a larger spatial extent was needed to adequately examine spatial patterns, so I measured all live or dead tree structures including stumps, snags, and windfallen trees that grew to at least breast height across the entire 2.59 ha plot. Spatial coordinates of all tree structures were obtained with a surveying laser.

To determine tree ages, and thus examine recruitment patterns, all tree structures were given an age designation as follows: pre-harvest (center date ≤1894 at 40 cm above ground) or post-harvest (center date > 1894). All live trees given a pre-harvest age

designation were cored at 40 cm, as were 20% of the post-harvest trees. Trees were cored repeatedly wherever increment cores were distant from the pith or where rot was encountered. Increment cores were mounted, surfaced, ring-counted, and/or crossdated using standard dendrochronological techniques (Stokes & Smiley 1968; Swetnam & Dieterich 1985). When the increment core failed to intercept the pith, or where the pith was rotten, the number of years from the innermost ring to the pith was estimated with a pith locator (concentric circles matched to the approximate curvature and density of the remaining inner rings).

Stand Structural Scenarios

I examined the spatial patterns of three stand structural scenarios: (1) 'unharvested' (1909 stand structure as it would have been if selective harvesting had not occurred in 1894); (2) 'harvested' (actual 1909 stand structure); and (3) 'contemporary' (actual 2002 stand structure). I restricted my attention to trees ≥9.14 cm DBH because detailed historical data were not collected for smaller trees. All tree spatial coordinates were obtained during contemporary measurements. The historical stem map was used to verify that trees and stumps present at plot establishment were located correctly.

To compare stand structure and spatial patterns among scenarios, I used the location (x-y coordinates), historical stem-map, and DBH of all trees and stumps (reconstructed) in each scenario. DBH data for the contemporary scenario were obtained during contemporary measurements, and data for the harvested scenario were obtained from the 1909 stem map and plot ledger. For the unharvested scenario, I needed to account for the trees that were harvested in 1894. Decomposition rates are slow in this

area (Jenny et al. 1949; Hart et al. 1992; Covington & Moore 1994), and most stumps and other dead materials were still present on the site. I measured the current diameter at soil surface of each stump, using evidence of past tree size such as rings of residual bark at the soil line, sapwood, and/or immovable rocks (designating a permanent root collar boundary) to aid in the measurement. A regression model using diameter at soil surface for similarly-aged trees was used to predict the DBH of each harvested tree in 1894 (Chapter 3).

Describing tree spatial patterns

Since spatial patterns are scale-dependent, I described the spatial patterns of trees and patches (groups of trees) at multiple scales on the 2.59-ha permanent plot for all three scenarios. I also described the tree recruitment and pine seedling establishment patterns. I used a variety of statistical techniques, because as with traditional statistics, one technique will not answer all research questions. Therefore, I used univariate point pattern analyses to answer questions regarding the spatial arrangement of trees and their patchy nature. I applied bivariate point pattern analysis and geostatistical techniques to analyze pine seedling recruitment patterns.

To determine whether the spatial pattern of individual trees changed with scale observed, I used point pattern analyses. Point pattern analyses are statistics that explore the mapped positions of points (trees) on a plane to determine whether their distribution is random (also called complete spatial randomness or CSR), aggregated, or uniform (Upton & Fingleton 1985; Legendre 1993). Two commonly-used point pattern techniques are nearest neighbor distance (NND) indices and second-order statistics. The

NND index presented in this study is Clark and Evans' R (Clark & Evans 1954), which examines the distribution associated with distance from a randomly selected tree to its first nearest neighbor. This index has been reported in other studies of southwestern ponderosa pine forests (Cooper 1961; White 1985), and I used it to directly compare my results with those studies. I corrected for edge effects and used z-tests to determine whether spatial distributions were significantly ($\alpha = 0.05$) non-random.

The second-order statistic I used, the Ripley's K(t) function (Ripley 1976; 1977; 1981), examines the spatial pattern of pairs of points within various radial lag distances (t) and does not aggregate spatial data. Therefore, Ripley's K(t) can quantify the intensity (density of points per unit area) of pattern at multiple scales (Upton & Fingleton 1985; Dale 1999). I used 2-m lag distances and a maximum lag distance of 80 m (half the minimum dimension of the plot; Boots & Getis 1988) to reduce the error induced by edge effects. Visual interpretation was simplified using a square root, variance-stabilizing transformation of K(t) to L(t)-t (Besag 1977). The observed K(t) values were tested for significance at $\alpha = 0.05$ using 99 Monte Carlo permutations (Upton & Fingleton 1985). All univariate point pattern analyses were analyzed using Reich and Davis's online spatial package (Reich & Davis 1998) in S-Plus 6.1 (Insightful Corp., Seattle, WA, 2002).

If the trees exhibited even-aged size characteristics, I would expect low variability in tree sizes within patches (Cooper 1960). Alternatively, I would expect high variability in tree sizes within uneven-aged patches (White 1985). These hypotheses were tested for each of the stand structural scenarios by examining the spatial dependence of individual tree size (DBH) using the index of spatial autocorrelation known as Moran's I (Moran

1950; Legendre & Legendre 1998). Each correlogram (plot of the Moran's I coefficient against lag distance) was tested for global significance; individual autocorrelation statistics ($\alpha = 0.05$, Bonferroni corrected to account for number of distance classes) were tested only when the global test was significant (Legendre & Legendre 1998). The lag distance was set to 5 m so that results were directly comparable with Biondi et al. (1994). Spatial autocorrelation analysis was conducted in the *R v.2.2.0* (R development Core Team, 2005) software environment using the *spdep* package (Bivand & Gebhardt 2000).

Describing tree recruitment patterns

In addition to the spatial pattern of individual trees, I was also interested in the seedling recruitment patterns observed after the 1894 harvest; and more specifically, I wanted to know where the pine seedlings became established relative to 1) pre-harvest trees, 2) natural openings in the stand, and 3) openings created by harvesting. I hypothesized that pine seedlings would establish in canopy gap openings, either natural or created by harvesting. Lastly, I was interested in whether these openings would be filled by pine seedlings all at once or whether recruitment might occur in multiple, distinct cohorts. To answer these questions, I treated the established, older trees (pre-harvest trees in 1894) as one population and the trees that came in since the harvest as a second population. Ripley's $K_{12}(t)$ bivariate analysis (Lotwick & Silverman 1982; Rowlingson & Diggle 1993; Diggle 2003) was used to examine the relationship between these two populations. Ripley $K_{12}(t)$ bivariate statistic is computed and interpreted in the same manner as the Ripley's K(t) statistic, except that distances are calculated between points from different populations and the confidence envelopes are formed by holding the

established tree and/or stump locations constant while simulating 99 toroidal shifts of the recruited pine tree locations. This step tested a variation of the independent point processes hypothesis (Goreaud & Pélissier 2003) focusing on the spatial patterns of the observed pine recruitment over time given the spatial pattern of the already established trees (or antecedent conditions [McDonald et al. 2002; 2003]). Ripley's $K_{12}(t)$ bivariate analysis was conducted using *R v.2.2.0* and the *splancs* package (Rowlingson & Diggle 1993; Bivand & Gebhardt 2000).

To further investigate whether the canopy gaps or openings were filled all at once and to visualize the recruitment of specific tree cohorts, I used geostatistical techniques called semivariogram analysis (plot of the semivariance against lag distance) and block kriging. Semivariance is half the averaged squared difference of all pairs of points separated by a given lag distance (Rossi et al. 1992). The key points of interest in an empirical semivariogram are the range (the lag distance at which the asymptotic value of the semivariogram is reached), sill (the semivariance associated with the asymptotic value of the semivariogram), and nugget (the semivariance when the lag distance is 0). While some advocate the Gaussian model for fitting semivariograms derived from demography data (Isaaks & Srivastava 1989; Biondi et al. 1994), I also fit exponential and spherical semivariogram models using the ordinary least square method (Cressie 1993; Bailey & Gatrell 1995).

Lastly, I used block kriging to aid in the interpretation of tree establishment dates and pattern. Block kriging is an application of the modeled semivariogram to interpolate or predict a variable of interest over an area (block) not measured originally. On a map produced by block kriging, individual tree establishment dates are interpolated across the

site (for 5x5 m predictions or blocks) and smoothed contours delineated areas with similar establishment dates. On this map, closer contours indicated greater variation in establishment dates. Semivariogram analysis was conducted and the corresponding kriged map was generated using *R v.2.2.0* and the *geoR* package (Ribeiro & Diggle 2001).

Results

Tree spatial patterns

The 1894 harvest removed approximately one third of the trees and two-thirds of the stand basal area (Table 2.1). The majority of the trees left after harvest were located in the southern and easterly portions of the plot, and were smaller in size than those removed by the harvest (Fig. 2.2). By 2002, tree density had increased six-fold and basal area had more than doubled compared to unharvested conditions.

Live trees were significantly aggregated under all scenarios (Table 2.1; see also Fig. 2.2) with trees being the most strongly aggregated in the harvested scenario. The contemporary scenario appeared to be significantly aggregated, but the characteristics of the patches differed from those observed in 1909 (see below). Trees in the contemporary scenario were much closer together (mean NND = 1.9 m) than in 1909 (mean NND = 4.5 m and 3.9 m in the unharvested and harvested scenarios, respectively).

In the unharvested and harvested scenarios, the data exhibited a distinct peak in aggregation at 6 to 8 m lag distances (Fig. 2.3a,b), indicating that patches of trees were approximately 0.02 ha to 0.03 ha in size (Table 2.1). However, the height of this peak was much larger for the harvested than unharvested scenario. In addition, in the

unharvested scenario, trees were aggregated up to 28 m and randomly distributed at all scales greater than 28 m. In the harvested scenario, trees were aggregated from 0 to 36 m and again from 40 to 76 m (Fig. 2.3b). In the contemporary scenario, distinct small patches were no longer discernable and trees remained aggregated at all spatial scales up to the maximum distance tested (Fig. 2.3c).

Trees of similar size were more likely to be near one another than expected by chance alone for all three scenarios ($p \leq 0.001$, 0.026, and ≤ 0.001 for unharvested, harvested, and contemporary, respectively). The Moran's I statistic indicated that individual trees were positively autocorrelated with respect to tree diameter, though this was significant only at short distances in 1909 (lags up to 15 m in the unharvested scenario, 5 m in the harvested scenario) and at much greater distances in 2002 (lags up to 30 m) (Fig. 2.4). Correlation between individual tree diameters was much more variable in the harvested scenario (Fig. 2.4b) than in unharvested scenario (Fig. 2.4a).

Tree recruitment patterns

Pine recruitment was aggregated in the early 1900s. Pine seedlings that established after 1894 established first in the grass openings and later around the stumps, and under the pre-harvest trees.

Ripley's $K_{12}(t)$ bivariate analysis (Fig. 2.5a) suggests that recruitment since the plot establishment was: (1) repulsed or negatively associated with unharvested tree locations up to 28 m (Fig. 2.5b) and randomly associated beyond 28 m; (2) randomly associated with the cut stump locations at lag distances under 8 m (Fig. 2.5c); and (3) attracted or positively associated beyond 8 m. The strength of repulsion with pre-harvest

trees peaked at 8 m, which corresponds to the peak in aggregation observed with Ripley's K(t) for the unharvested and harvested scenarios and the shift from random to positive association with the cut stumps present after the 1894 harvest (Fig. 2.5c).

Of the 493 trees cored, six were not dated to center due to rot and/or broken cores. For those trees that were successfully dated to center, the average number of years from the innermost ring to the pith was 4.4 years (SD = 3.3).

Contemporary conditions (2002), 108 years after the initial harvest, exhibited an uneven-aged distribution composed almost exclusively of cohorts that established within 40 years of the 1894 harvest (Fig. 2.6a), and were spatially less variable (more similar) at lag distances up to 22.4 m (Fig. 2.6b). An exponential semivariogram model fit the contemporary tree age data best (Fig. 2.6a, b) and was used to produce a kriged map (Fig. 2.6c) illustrating tree recruitment patterns across the plot. Following harvest, initial cohort recruitment occurred in the middle of the openings between patches of unharvested live trees first. Subsequent cohorts (1908-1918) established progressively closer to these trees, often in the growing spaces created in the 1894 harvest. During the next two decades (1923-1938), the few cohorts that established, did so on sites not fully occupied by previous recruitment.

I tested the possibility that wide establishment peaks were an artifact of imprecision in the center date estimation method. For that purpose, I selected a subset of samples that either intersected the pith or were within an estimated 5 yr of center (121 out of 277 or 44% of the total number of dated trees). This highly reliable subset had peaks of establishment as broad as the full post-harvest data set (1894-1954), with 57% of the establishment dates occurring prior to 1919 and 42% occurring in 1919 or after. Given

the high probability that almost all of the 1919-1938 trees actually germinated in 1919 (Savage et al. 1996) and the lack of trees in the subset of samples with center dates after 1938 (1%), these results suggest that the imprecision in estimation of germination date due to sampling at stump height is contained within 20 yr. Thus, the three broad peaks (Fig 2.6a) of post-harvest tree establishment, in sum, appear to represent a true range of establishment dates, rather than being artifacts of the sampling or analysis methods.

Discussion

Tree spatial patterns

I found that trees were aggregated into groups, prior to selective harvesting in 1894. Historically, unharvested stands on this study site were composed of tree groups or patches averaging 0.02 ha in size with sparsely populated zones between patches. Under current conditions, the site may be characterized as a single patch composed of similarly sized, small trees spanning the entire area.

The unharvested presettlement (old-growth) pine group sizes I found were smaller than those reported by Cooper (1961) and on the lower end of the range reported by White (1985). Cooper (1961) found that trees in east-central Arizona were aggregated into distinct groups ranging from 0.06 to 0.14 ha. While Cooper concluded that trees in younger stands ($\leq$44 years) had a tendency to be arranged randomly and that trees in older stands (~ 80 years) tended to be more regularly (uniformly) distributed, only two of his 14 stands were statistically different from random. White (1985), who conducted his study in the nearby Gus Pearson Natural Area, determined that stems of old ponderosa pine trees (live trees with center dates $\leq$1875) were strongly aggregated and occupied

areas averaging 0.1 ha (range: 0.02 to 0.29 ha). The reason for the differences in group size between Cooper (1961), White (1985), and this study is most likely the method by which a group or patch was designated (i.e., at least 2 or 3 trees, for example), as this was different in all three studies. Yet, differences in soil type, parent material, climate, and land-use cannot be ruled out. Finally, the patch size and aggregation results reported for presettlement (old-growth) tree groups in Arizona differ from those reported in other regions. In the Colorado Front Range, Boyden et al. (2005) and Mast and Veblen (1999) reported a random and/or regular overstory patterns for ponderosa pine in old-growth and grassland ecotone stands, respectively. In old-growth ponderosa pine stands of eastern Oregon and California, Youngblood et al. (2004) observed both aggregated and random spatial patterns.

My results showed that the initial harvest in 1894 did not affect tree group or patch size. The patch sizes in the unharvested scenario were the same as after the initial harvest. This may explain why my tree group sizes were similar to White's (1985) results even though he did not include stumps in his study. Over the last 100+ years, however, tree group size has increased and the study area has become one large group or patch. This increase in tree density over time was due to an increase in the number of tree groups (recruitment of new groups or patches) rather than tree recruitment into pre-harvest groups, which is consistent with findings of Biondi et al. (1994). Spatial autocorrelation between tree diameters was also more variable in the harvested than in unharvested scenario, indicating that while the 1894 harvest decreased the variation in tree diameters (trees were similar in size) within groups or patches; it also altered the spatial arrangement of trees within patches.

The partial harvest in 1894 exaggerated the already patchy nature of this forest and homogenized the plot with respect to tree size by removing many of the largest diameter trees (Moore et al. 2004). However, the impact of the 1894 partial harvest on spatial patterns varied with scale. At fine scales (smaller extents $\leq$28 m), tree group or patch size was largely unaffected. At coarser scales (larger extents > 28 m), the patchiness of the residual trees was increased because the harvest not only removed the large trees scattered randomly about the plot but also removed many of the large patches entirely. In summary, even though the tree group or patch size was not affected by the 1894 harvest, the number and spatial arrangement of tree groups was greatly affected.

Tree recruitment patterns

I was interested in how the residual stand structural patterns influence the recruitment of subsequent ponderosa pine cohorts; and specifically, I wanted to know where these cohorts established. My results suggested that pine establishment in this area was highest in interspaces or canopy gap openings, which is consistent with findings from numerous other studies (Pearson 1923, Cooper 1960; White 1985; Mast & Veblen 1999; Boyden et al. 2005). The tree recruitment patterns that I found are consistent with Watt's (1947) 'gap' model, as suggested by Stephens and Fry (2005).

A unique finding of my study was that post-harvest recruitment patterns were not spatially random and pine seedlings initially established near the center of natural grass openings, and later filled-in the remaining available growing space in the grass openings and around the stumps created by the 1894 harvest. While canopy gaps are known to be important for tree recruitment in shade intolerant species, my results showed that the

harvested sites were somewhat less likely to promote new recruitment into the stand. The fact that the pine seedlings established first in the middle of grass openings is likely the product of many years of livestock overgrazing, which effectively eliminated the competition of herbaceous plants with pine seedling (Pearson 1942; Heidmann et al. 1982). The study site was fenced in 1909, which in turn, released already-established seedlings from trampling and/or browsing (Bakker 2005). Lastly, I saw multiple post-harvest pine cohorts establishing in the study area, and the site was not dominated by a single cohort as suggested by Savage et al. (1996). Since Savage et al. (1996) study area was only 0.1 ha in size, they likely only sampled within one of these pine seedling patches, and did not capture the full range of cohorts.

Conclusions and Management Implications

Spatial analysis of structural characteristics and recruitment patterns permits the reconstruction of stand development for a stand. In this ponderosa pine stand, it provided valuable insight into the long-term consequences of previous management actions and regeneration episodes. By applying various analysis techniques to spatially-explicit data, detailed information can be derived on key variables (i.e., tree density, mean NND, patch size) that may, in turn, be applied in restoration efforts. By conducting such analyses over time, I developed a spatial and temporal understanding of pine establishment patterns, possible driving mechanisms, and the impacts of human disturbance (Foster et al. 2003) within ponderosa pine forests of north-central Arizona.

My findings with respect to within-patch variability and patch size are limited by the area sampled, and should be investigated at larger extents (i.e., larger stands,

watershed- or landscape-scale). In addition, the majority of studies that have examined southwestern ponderosa pine regeneration patterns have occurred within a mile of one another on relatively productive soils of basalt parent material (Pearson 1923, White 1985; Biondi et al. 1994; Savage et al. 1996; Mast et al. 1999; Kerns et al. 2003). Further investigation is needed to determine if patch size and pine seedling recruitment patterns found in these studies can be extrapolated to other soil types and parent materials. Only then can I make generalizations and explore possible mechanisms and processes behind the spatial patterns.

The physical legacy of presettlement tree and spatial patterns is still present on many landscapes, but may not be obvious to the casual observer. Past management activities (i.e., harvesting, livestock grazing, fire exclusion) and the natural progression of stand dynamics often obscure presettlement tree patterns. It is true that forest thinning activities that do not use presettlement tree evidence will likely result in a forest structure less susceptible to catastrophic fire events. However, forest restoration activities that use presettlement tree evidence to guide their activities will also maintain a spatial pattern that may be linked to other long-term processes such as tree regeneration, competition, and mortality. In addition, studies that have examined other ecosystem restoration targets such as understory plant production (Laughlin et al. *In press*) or wildlife habitat (Patton 1977; Graham et al. 1994; Meyer & Sisk 2001; Waltz & Covington 2003) have reported that tree spatial pattern is important to these resources.

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Table 2.1. Stand level structural and spatial attributes for trees ≥9.14 cm DBH on COCS1A for unharvested (1909), harvested (1909), and contemporary (2002) scenarios.

Attribute	Unharvested	Harvested	Contemporary
Structural			
Diameter at Breast Height (cm)			
Mean ± SD	44.0 ± 18.1	35.6 ± 13.4	26.1 ± 13.3
Minimum	9.5	10.2	9.1
Maximum	105.0	76.2	86.6
Density (TPH)	85	52	575
Basal Area (m^2/ha)	15.1	5.8	38.6
QMD (cm)	47.6	38.0	29.3
Spatial			
Nearest Neighbor Distance (m)			
Mean ± SD	4.5 ± 3.7	3.9 ± 3.6	1.9 ± 1.2
Median	3.3	2.6	1.6
Minimum	0.9	1.0	0.0
Maximum	16.2	19.2	11.9
Clark & Evans R[1]	0.83[1]	0.55[1]	0.90[1]

[1] Values significantly different from complete spatial randomness at the 95% confidence level

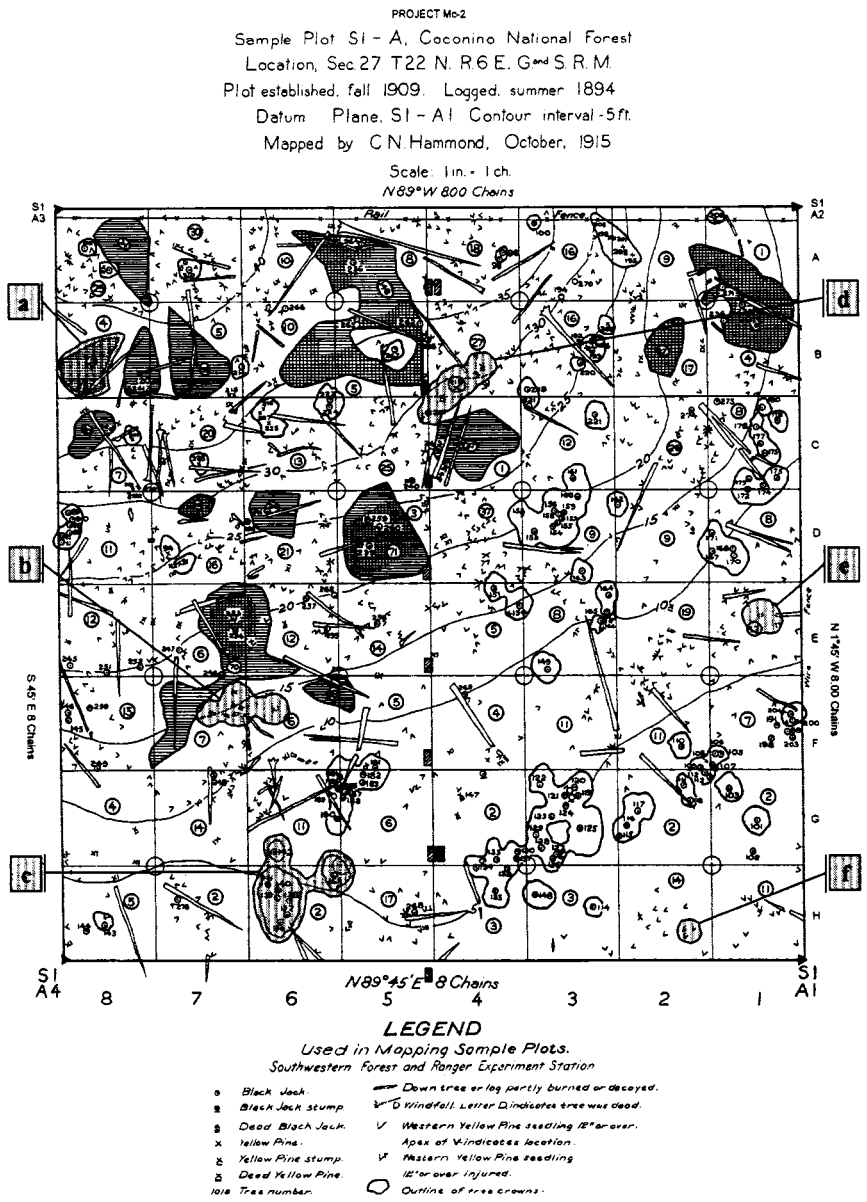

Figure 2.1. Example stem map of COCS1A (data collected 1909; map drafted 1915). Features to note include: (a) patches of dense regeneration (crosshatching indicates variation in seedling patch densities) (b) harvested tree groups or patches (all trees harvested), (c) locations of groups and single live trees ≥ 9.14 cm DBH, (d) selectively harvested tree groups or patches (not all trees harvested), (e) selectively harvested single trees and (f) location of individual pine seedlings. Legend terms defined in Moore et al. (2004). *Redrawn with permission.*

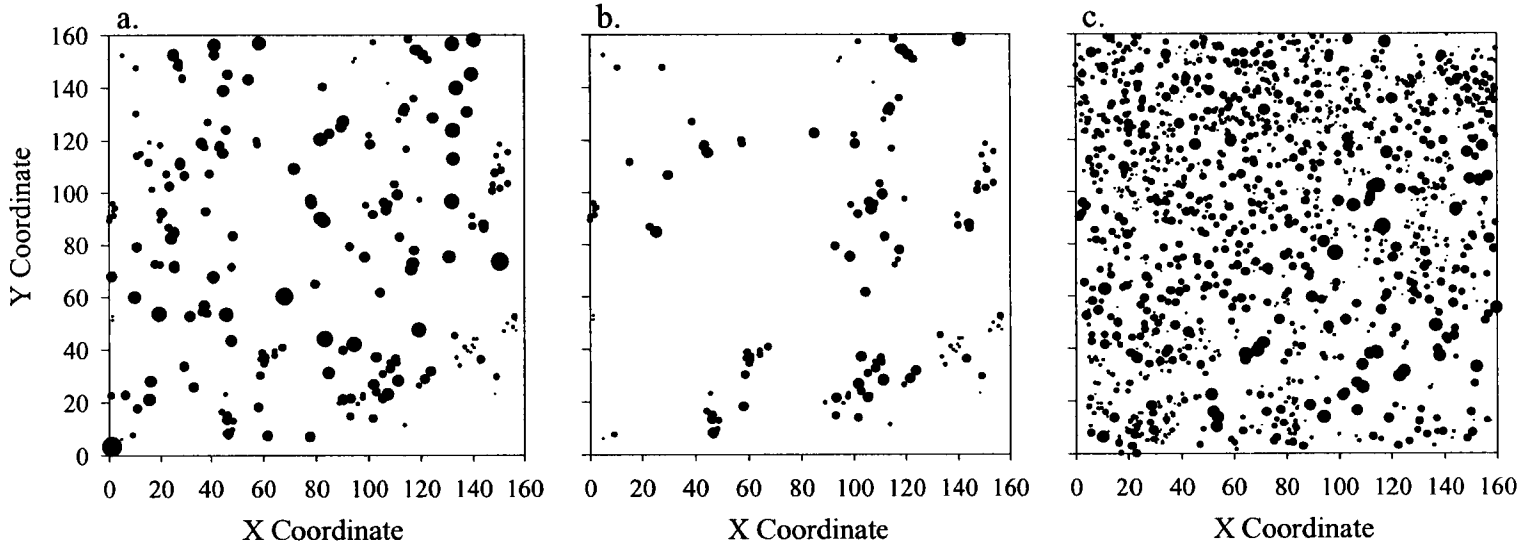

Figure 2.2. Stem maps from COCS1A of live trees ≥9.14 cm DBH in three scenarios: (a) unharvested (1909 stand structure as it would have been if selective harvesting had not occurred in 1894, n = 219), (b) harvested (actual 1909 stand structure, n = 134), and (c) contemporary (actual 2002 stand structure, n = 1,487). Point size is proportional to stem diameter and on a different scale from tree coordinates for visual clarity.

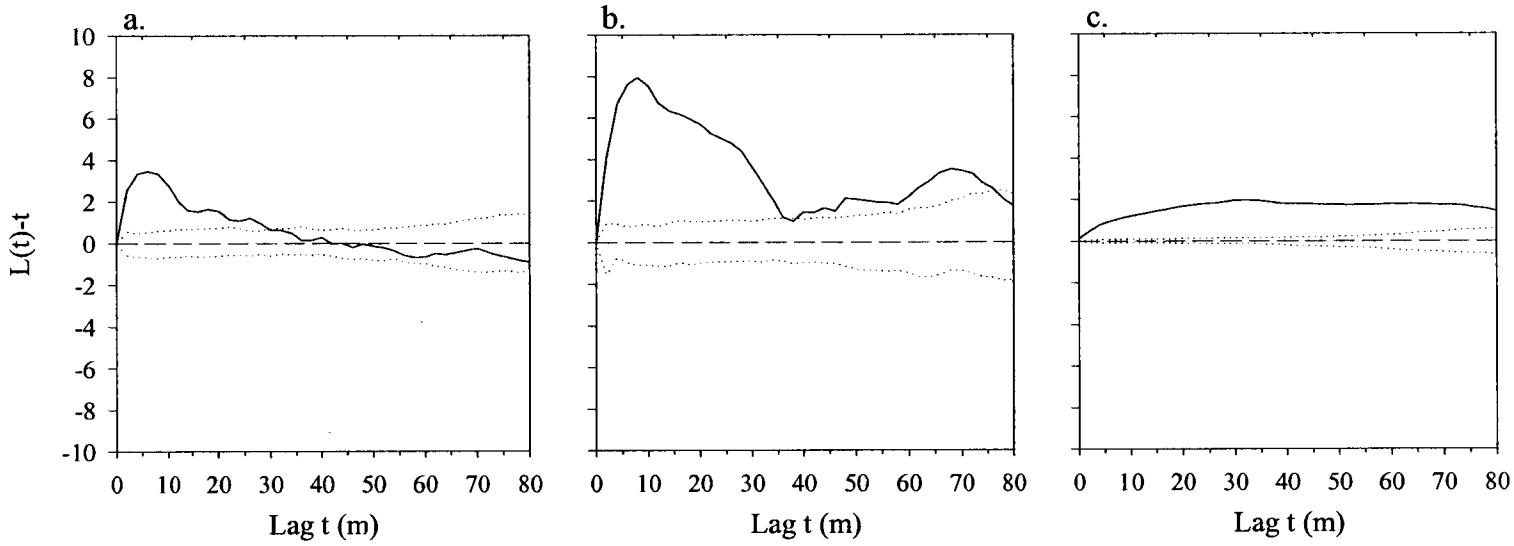

Figure 2.3. Ripley's K(t) univariate statistic (transformed as [L(t)-t]) as a function of lag distance for COCS1A: (a) unharvested (1909), n = 219; (b) harvested (1894 harvest; mapped 1909), n = 134; (c) contemporary (2002), n = 1,487. The horizontal dashed line is the expectation under CSR (random) and the dotted lines on either side of it are the 95% confidence limits. Calculated values that fall outside of the confidence interval are statistically significant; values > 0 indicate aggregation and values < 0 indicate uniform (regular) spatial distribution.

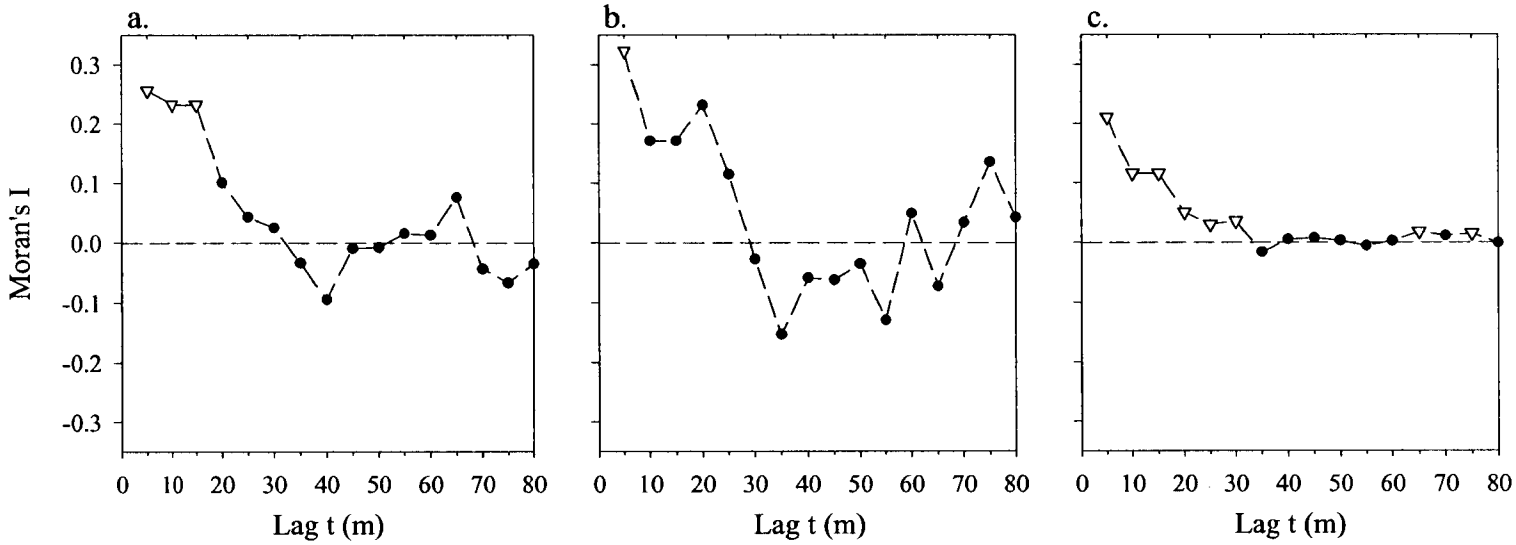

Figure 2.4. Correlograms of Moran's I against lag distance for COCS1A: (a) unharvested (1909), n = 219 (b) harvested (1894 harvest; mapped in 1909), n = 134; (c) contemporary (2002), n = 1,487. The variable analyzed was tree DBH (cm; trees ≥9.14 cm DBH). Values may range from +1 (perfect positive spatial correlation) to -1 (perfect negative spatial correlation); 0 indicates no spatial correlation. Triangles indicate lag distances with significant autocorrelation ($\alpha = 0.05$, Bonferroni corrected), and black dots are not significant.

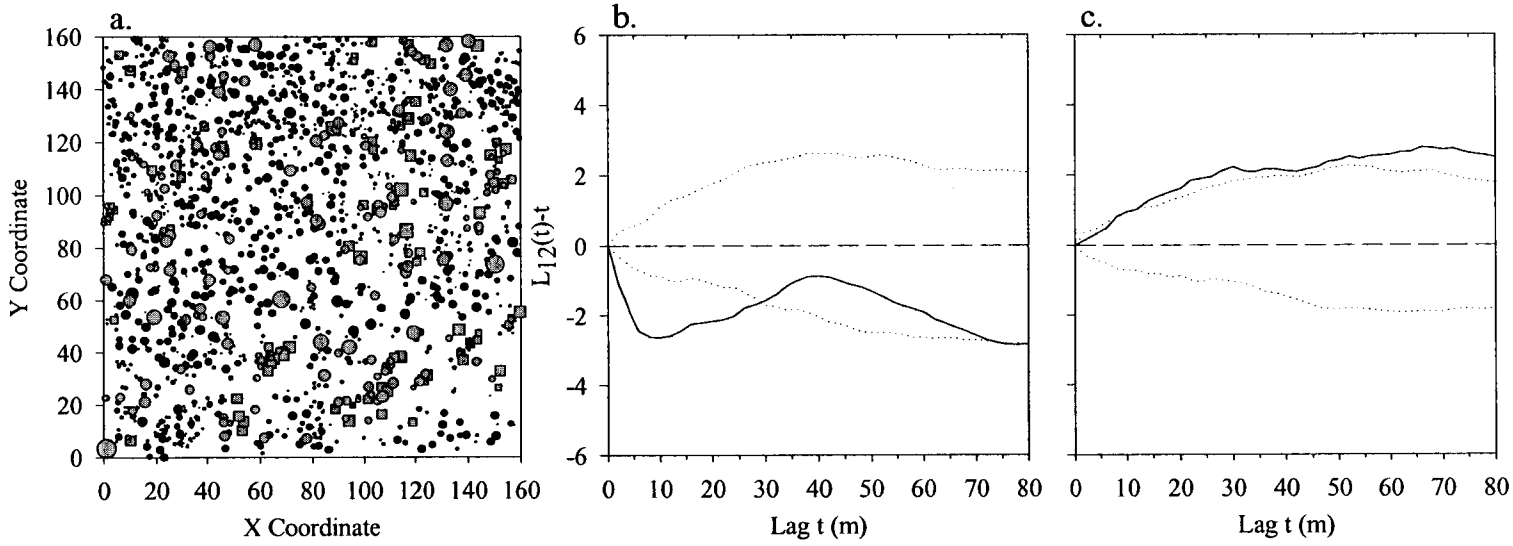

Figure 2.5. (a) COCS1A stem map showing locations of post-harvest trees (center date ≥ 1894 at 40 cm above ground level, black circles, n = 1405) from the contemporary scenario (2002) with respect to live trees (grey squares, n = 134) and cut stumps (grey circles, n = 85) in 1909 and the resulting Ripley's $K_{12}(t)$ bivariate statistic (transformed as $[L_{12}(t)-t]$) as a function of lag distance (t) is shown for the comparison of post-harvest recruitment patterns to (b) pre-harvest trees and (c) cut stump locations in 1909. The horizontal dashed line is the expected line under CSR (random) and the dotted lines on either side of it are the 95% confidence limits from simulating 99 toroidal shifts of the post-harvest tree locations. Calculated values that fall outside of the confidence interval are statistically significant; values > 0 indicate attraction and values < 0 indicate repulsion between the two populations.

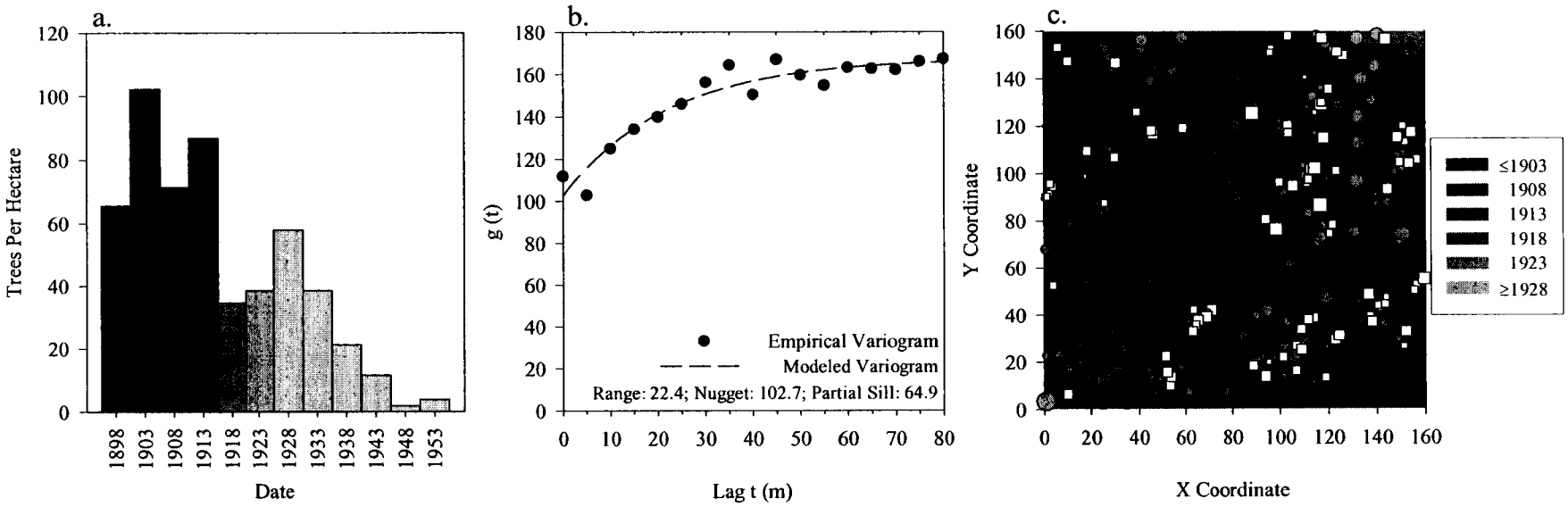

Figure 2.6. COCS1A (a) age distribution derived from 20% (n = 277) subsample of post-harvest (center date ≥ 1894 at 40 cm above ground level) trees, (b) semivariogram of post-harvest tree age against lag distance, and (c) kriged contour map of post-harvest tree establishment patterns (age on 5x5 m blocks). Darkest areas indicate where trees established immediately following harvest, progressively lighter tones of grey indicate areas of successive cohort establishment, with the lightest grey tone indicating the last locations where establishment occurred. White squares are the pre-harvest trees and grey circles are the cut stumps cut in 1894 and mapped in 1909. Note that the same shading pattern is employed in the age distribution and the kriged map.

Chapter 3

Using Historically Stem-Mapped Permanent Plots to Quantify Reference Conditions in Ponderosa Pine Forests of North-Central Arizona

Abstract

Forest structural reference conditions are used to understand how ecosystems have been altered and to guide restoration and management objectives. I utilized nine historically stem-mapped, permanent plots established in the early 20th century, which contain detailed information on stumps, snags, and logs, to develop a reconstruction model and provide precise reference conditions for ponderosa pine forests of north-central Arizona prior to Euro-American settlement. Reference conditions for these plots in 1873-1874 included the following historical attributes: tree densities of 45-127 trees ha^{-1}, mean tree dbh of 43.8 cm with a corresponding QMD range of 41.5-51.3 cm, and a stand basal area of 9.2 to 18.0 m^2 ha^{-1}. On average, historical dead structures (snags and logs prior to Euro-American settlement) were found to have a combined density of 4.7 trees ha^{-1}. The reconstructed diameter distributions (for live ponderosa pine trees with dbh $\geq$ 9.14 cm) prior to fire exclusion varied in shape, but generally displayed an irregular, uneven-aged size distribution with one or two dominant size cohorts.

I suggest that specific management objectives for the structural restoration of ponderosa pine forests of north-central Arizona should emphasize: (1) conservation and retention of all presettlement (> 130 years) trees; (2) reducing tree densities with the

restoration objective of 50-150 trees ha $^{-1}$ where the corresponding large tree component is 50-25% of the total trees ha^{-1}, respectively; (3) manipulation of the diameter distribution to achieve a unimodal or irregular, uneven-aged shape (possibly targeting a balanced, uneven-aged shape on cinder soils types) through the use of harvest and thinning practices which mimic gap disturbances (i.e., individual tree selection system); and (4) 3 to 11 structures ha^{-1} (snags and logs) resulting from natural mortality with appropriate increases in snag and log densities where live tree densities increase.

Introduction

Forest conditions prior to Euro-American settlement of the Southwestern United States have been promoted for understanding how ecosystems have been altered (Kaufmann et al. 1994, Morgan et al. 1994, Fulé et al. 1997, Moore et al. 1999). Approaches that emphasize management of forests within their natural range of variability try to determine what presettlement forest conditions were, and what caused contemporary conditions to differ from that historical range (Kaufmann et al. 1994, Morgan et al. 1994, Swanson et al. 1994, Covington et al. 1997, Fulé et al. 1997, Landres et al. 1999, Taylor 2004). Restoration projects in ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum*) forests of north-central Arizona have been guided by an assumption that the use of reference conditions will maintain important ecosystem structure and function, which in turn reduce the risk of wildfires and insect or disease epidemics (Swanson et al. 1994, Landres et al. 1999, Moore et al. 1999, Allen et al. 2002). In many cases where contemporary forests have been degraded and conditions are outside their range of natural variability, reference conditions also serve to guide

silvicultural treatments (Morgan et al. 1994, Fulé et al. 1997, Moore et al. 1999, Swetnam et al. 1999). Thus, identification of suitable reference conditions is an essential step in the ecosystem restoration planning process (Kaufmann et al. 1994, Arno et al. 1995, Fulé et al. 1997, Covington et al. 1997).

North-central Arizona's ponderosa pine forests have been dramatically altered by Euro-American land-use practices. It is widely accepted that more than a century of fire exclusion and/or suppression, past livestock grazing and logging practices have resulted in degradation of forest structure, function, and processes, causing these forested systems to become highly susceptible to catastrophic fire and pest outbreaks (Covington and Moore 1994a, 1994b, Johnson 1994, Allen et al. 2002). With the passing of the national Healthy Forest Restoration Act (HFRA) of 2003, policy is now in place to facilitate actions that will restore these systems, thus reducing their susceptibility and risk to disturbance events outside their natural range of variability. However, restoring and sustaining highly altered forest ecosystems remains a major challenge for forest managers in north-central Arizona.

Presettlement (circa 1876 [Dieterich 1980]) ponderosa pine forest structure descriptions developed for north-central Arizona are based on historical ecology techniques (Egan and Howell 2001) including written and oral historical records (e.g., Beale 1858), historical photographs (e.g., Swetnam et al. 1999, Kaufmann et al. 2001), early forest inventories (e.g., Lang and Stewart 1910), and/or dendrochronological studies (e.g., Fulé et al. 1997). The cultural accounts and early inventories only provide a general context, which rarely translates into viable management objectives, and can not be expected to fully characterize forest structure by today's statistical standards. While

dendrochronological techniques have been applied with more success (e.g., White 1985, Covington and Moore 1994a, Fulé et al. 1997, Covington et al. 1997, Mast et al. 1999, Waltz et al. 2003) (Table 3.1), these studies attempt to reconstruct presettlement structure over a century of forest change, and the flexibility of coarse assumptions needed to fill the significant information gaps over such long periods of time are unknown.

Moore et al. (2004) quantified over 80 years of change in forest structure and composition on 15 historically, stem-mapped, permanent plots established in the early 1900s by the United States Forest Service (USFS) in Arizona and New Mexico. In this paper, I used five of the above plots and one additional plot, all of which were located in ponderosa pine forests on the Coconino National Forest, to develop a reconstruction model and improve the precision of reconstructed reference conditions for these sites. The specific research questions addressed in this study were: (1) What were the presettlement forest reference conditions (including both live and dead trees) for ponderosa pine forests of north-central Arizona? (2) How do these reconstructions compare to other studies where dendrochronological techniques or historical forest inventory data were the only methods used? (3) How can land managers incorporate this information into their current and future land management goals?

Methods

Project History and Study Site Location

A series of permanent plots were established between 1909 and 1913 to quantify growth and mortality rates at both the individual tree and stand level in order to resolve

issues surrounding the effects of harvesting and slash disposal practices on the natural regeneration of ponderosa pine (Woolsey 1911, 1912, Pearson 1923, 1933). Additional mechanisms influencing regeneration and stand dynamics also monitored included various levels of herbaceous competition and shade effects, soil type, and both natural and anthropogenic disturbances (e.g., livestock grazing, fire, lightning, herbivory and pests) (Pearson 1950). These permanent plots are described in great detail by Moore et al. (2004), who used these and others to quantify forest structural (tree density, size, spatial arrangement, and age) and compositional changes observed between the original plot establishment date and contemporary remeasurement dates throughout Arizona and New Mexico.

General Description of Individual Plots

In this section, I describe the general characteristics of the six individual plots used in this study. I follow the original identification system that used a combination of letters and numbers representing the Fort Valley Experimental Station silvicultural unit (*S1, S2*, etc.) and individual permanent plot designations (*A, B*, etc.). These plots were established before R.A. Fisher (1925) presented randomization as an essential component in the design and analysis of experiments. Plots were located within areas where timber sales had recently occurred (ideally within 5 years) and were 2 to 6 ha (5-15 acres) in size (Woolsey 1912).

S1A and S1B: These two pure ponderosa pine plots were established in 1909 and are 2.59 and 4.05 ha, respectively (Fig. 3.1). This area, including these plots, underwent private cutting around 1894, in which the objective was to leave 8 to 10 seed trees ha^{-1}

(Pearson 1923). That treatment is now known as a seed-tree harvesting system in which a few widely-spaced trees are retained after harvest to provide uniformly distributed regeneration (Nyland 1996). Soils are Mollic Eutroboralfs and Typic Argiborolls (Terrestrial Ecosystem Unit 582) representing approximately 7% (56,000 hectares) of the soils found on the Coconino National Forest (Miller et al. 1995). Topography is rolling and elevation is 2,225 meters. The herbaceous ground cover in 1909 was considered moderately dense, dominated by bunchgrasses, and closely grazed by cattle, sheep, and horses (Pearson 1923). Both plots were fenced at the time of their establishment to prevent livestock grazing.

S4A and S4B: These two pure ponderosa pine plots were established in 1909 and are 3.24 ha each. Both plots received a relatively light group selection harvest in 1909 (Krauch 1926, Pearson 1950) in which groups, or patches, of mature trees are removed to facilitate patchy regeneration patterns (Nyland 1996). After harvest, brush was piled but not burned. Similar to the *S1A* and *S1B* sites, soils are Mollic Eutroboralfs and Typic Argiborolls but one this site they covered by volcanic cinders (Terrestrial Ecosystem Unit 551) representing approximately 1% (11,000 hectares) of the soils found on the Coconino National Forest (Miller et al. 1995). Topography is gently rolling and elevation is 2,073 meters. Herbaceous cover was judged as sparse, mainly in the form of grasses, and lightly grazed by cattle and sheep. There is no record that these plots were ever fenced. Pine reproduction was deemed deficient (Pearson 1923).

S5B2 and S5B3: These plots were established in 1913 as part of a larger study comparing the results of several regeneration methods (group selection, seed tree, light selection [shelterwood], and the Wagner border method; Krauch 1923, 1926, 1933,

Pearson 1923) in ponderosa pine systems. These plots were harvested in 1909 as follows: plot *S5B2* used a seed tree regeneration cut and *S5B3* used a light group selection. This area is dominated by ponderosa pine with some (<10% of the contemporary basal area) Gambel oak (*Quercus gambelii* Nutt.). Plots are 1.21 ha each and the soils are predominantly Lithic Eutroboralfs and Mollic Eutroboralfs, with some Lithic Argiborolls. These soils (Terrestrial Ecosystem Unit 585) represent just under 4% (31,000 hectares) of the soils found on the Coconino National Forest (Miller et al. 1995) and have a clay loam texture with a gently rolling topography. Elevation is between 2,195 and 2,256 meters. Herbaceous ground cover was judged moderately dense and closely grazed by cattle and sheep until the summer of 1919, when these plots were fenced to exclude livestock grazing (Pearson 1923). Krauch (1923) regarded these residual pine stands as "inferior to those reserved on other divisions" of the Coconino National Forest, but no mention of the varying oak component was included. The pine regeneration observed was deemed as "exceeding all expectations" (on *S5B2*) and "restocked" (on *S5B3*) by 1919 (Pearson 1950).

Field and laboratory methods

Historical (1909-1913) and contemporary (1999-2004) field methods for measuring these plots are detailed by Moore et al. (2004), who also reported stand structural changes within a 1.01-ha subplot of these and other permanent plots throughout Arizona and New Mexico. Additional field measurements collected for this study include tree diameter at soil surface (dss); bark thickness at dss (average of three measurements), and tree increment cores at breast height (1.37 m above ground). Tree increment cores were

mounted, surfaced, and crossdated using standard dendrochronological techniques (Stokes and Smiley 1968, Fritts 1971, Dieterich and Swetnam 1984, Swetnam and Dieterich 1985). Tree rings were counted on cores that could not be crossdated, especially in the case of younger trees. Where pith was missed, additional years to the tree's pith were estimated with a pith locator (Applequist 1958). A proportional method (Bakker 2005) was applied to reconstruct past tree sizes, based on the observed growth either prior to or immediately following initial harvest. An advantage of this method was that it provided for the differences in growth following early Euro-American harvests.

Reconstructing presettlement forest structure

In order to reconstruct forest structure prior to Euro-American settlement in north-central Arizona, I used ledger data and detailed stem-maps that precisely noted the location of structures recorded at plot establishment (e.g., Fig. 3.2), as well as contemporary data to reconstruct past forest structural conditions. To develop my model and accomplish these reconstructions, the following assumptions were needed:

a) Seedlings that established between Euro-American settlement (1876-1880) and plot establishment (1909-1913) would not have grown to be larger than 9.14 cm, the minimum diameter at breast (dbh) height measured at plot establishment, nor significantly competed with (altered the growth of) larger trees. These assumptions are supported by Cormier (1990) who found that seedlings took an average of 14 years to reach a height of 1.37 meters above ground on limestone soils and by the slow diameter growth of small trees reported by Krauch (1933).

b) On sites where the initial harvest did not coincide with plot establishment (S1A and S1B), trees that were not cut in the initial harvest would have grown at a slower rate until plot establishment because of the additional competition that harvested trees would have exerted. Southwestern ponderosa pine trees released from competition by harvest or other factors often have faster growth rates (Schubert 1971, Ronco et al. 1985, Ffolliott et al. 2000).

c) Natural tree mortality (snags and logs) as observed at plot establishment resulted from natural mortality agents (e.g., lightning, insects, pathogens, wind events). Natural mortality would have changed little between presettlement and plot establishment, when it was known to be an infrequent occurrence (indicated by the relatively few snags and logs observed at plot establishment). Lastly, natural mortality was independent of tree growth and size. These assumptions are supported by the low mortality rates observed by Fulé et al. (2001) at the Gus Pearson Natural Area (< 0.5 m^2/ha/decade) from 1920-1950, by Harrington (1996) and Chambers and Mast (2005) who observed no statistical differences in snag fall rates between size classes on sites in the San Juan and Kaibab National Forests, respectively.

d) All tree structures (e.g., live trees, snags, stumps, logs) present at plot establishment were tallied by the field crews and there were no errors in the original ledger and stem-map data.

Reference conditions are easiest to interpret and visualize when they correspond to a time prior to the onset of degradation commonly associated with Euro-American

settlement (Moore et al. 1999). For southwestern ponderosa pine forest, reference conditions often coincide with the complete exclusion of the natural frequent surface fire regime (Covington and Moore 1994a, Fulé et al. 1999, Mast et al. 1999, Waltz et al. 2003). The last recorded fire for the Gus Person Natural Area (GPNA) was estimated to have occurred around 1876 (Dieterich 1980). Similar fire exclusion dates were found for two ponderosa pine-mixed conifer stands of the nearby San Francisco Peaks (1892 and 1876) by Heinlein et al. (2005), an extensive study south of Flagstaff Arizona (1881) by Van Horne and Fulé (2006), and for sites near Bellmont, Arizona (1883) by Fulé et al. (1997).

I chose to reconstruct these plots just prior to initial harvests, which coincided with plot establishment for all sites other than S1A and S1B. On S1A and S1B, initial harvests occurred in 1894 and the plots were established 15 years later (1909), thus necessitating an additional post-harvest growth model. The addition of a post-harvest model was used to capture expected difference in growth resulting from the 1894 harvest allowing me to use the use historical ledger and stem-map data to reconstruct stand structure prior to initial harvesting. Then these resulting structures were reconstructed to a date prior to fire exclusion using site-specific, per-harvest growth models based on growth since Euro-American settlement.

I selected a fire exclusion date that both minimized the measurement error associated with tree growth and allowed the reconstruction of stand conditions at a common date prior to the fire exclusions dates reported in the literature (1876). To do so, I desired a simple model that could provide reconstructions in discrete five-year periods ending with a date prior to fire exclusion. I chose to reconstruct these plots to 1873 for S5B2 and

S5B3, and to 1874 for all other plots rather than 1876 for all plots. These dates were selected to: 1) ensure *S1A* and *S1B* would could be reconstructed in 1894, the year of initial harvesting, and 2) facilitate the use of the historical ledger data which was collected in discrete five year intervals, and 3) reconstructing stand conditions in 1876 would have required interpolating between two separate reconstructions dates. In addition, these reconstructions were selected as they were common dates known to be prior to fire exclusion in the area and I had no data suggesting different fire exclusion dates.

In this study, historical tree density and individual tree size were modeled using a reconstruction model composed of three steps including: 1) a reconstruction of forest structure prior to initial harvest; 2) estimating live tree sizes prior to the disruption of the natural fire regime; and 3) return of infrequent natural mortality events to the pine population. Each of these model steps are explained in more detail below. This study took advantage of the detailed data collected and stem-maps created at plot establishment, and only required estimating tree growth over a short period (35-40 yrs) and mortality dates for dead trees recorded at plot establishment.

The first step of this approach was dependent on whether the plots were established the year they were harvested or some time later and, thus, at what point the cut stumps should be treated as live trees and returned to the live tree population. The second step consisted of estimating the size of live trees in the past (including the harvested trees added during the previous step). This step was accomplished using the pre- and post-harvest relationships between tree diameter and the corresponding periodic basal area

increment as observed by trees present both at plot establishment (1909-1913) and contemporarily.

To estimate the dbh of harvested trees in the late 1800s, I used current evidence consisting of those trees' stumps in one of four decomposition classes (Maser et al. 1979). I developed a relationship between dss and dbh based on currently live trees present at plot establishment, with the dss of numerous stumps being estimated due to advanced decomposition. When available, I used bark rings, sapwood, immovable rocks, and mapped records of stump diameter (only for sites *S5B2* and *S5B3*) to obtain precise estimates of past tree size.

Because fall and decomposition rates for snags and logs are poorly understood (Harmon et al. 1986, Fulé et al. 1997, Mast et al. 1999), I used applied probability for the third step of the reconstruction process. In this step, I wanted to assign death dates to snags and logs so that structures whose death was after fire exclusion would be treated as live trees and thus returned to the live tree population (similarly to the stumps in step one). Once these trees were added to the live tree population, their past size was estimated using the same methods outline in step two (above). To accomplish this, I sampled contemporary snags and logs to determine their death dates (within five years) using notes on tree deaths from the ledger records. Given the contemporary condition (snag and log) and the ledger recorded death date, observations of the number of five-year time steps since death were made. These discrete, independent observations (of the number of five-year time steps since death for snags or logs) were then described using a geometric distribution, and maximum likelihood estimates of the corresponding population parameters, denoted p_{snags} for snags and p_{logs} for logs, were obtained for each

geometric distributions. In general, these population parameters quantify the probability that a snag or log was a live tree five years earlier. For individual snags and logs recorded at plot establishment, death dates were then determined by randomly drawing an observation (number of five-year time steps since death) from the corresponding geometric distribution with parameter p_{snags} or p_{logs}, and assigning it to that structure.

To assess the effect on presettlement forest reconstructions of assigning death dates at random and the application of the specific backgrowth equations, a sensitivity analysis was carried out by running 100 simulations of the reconstruction model using upper and lower interval estimated values for the geometric distribution parameters and the predicted previous five-year basal area increment.

Results

All linear regressions predicting past trees sizes (backgrowth equations) and dbh from dss provided good fits as judged by the distribution of residuals, but coefficients of determination were small and varied (Table 3.2). The regression coefficients used for predicting previous five-year basal area growth had a smaller intercept and steeper slope for both *S1A* and *S1B,* prior to harvest. Maximum likelihood estimates of the geometric distribution population parameter (p_{snags} or p_{logs}) derived from samples of the number of five-year time steps since death for the snags and logs present at plot establishment were estimated as $p_{snags} = 0.066$ (SE = 0.014, n = 22) and $p_{logs} = 0.059$ (SE = 0.012, n = 21), respectively. For example, a random sample (i.e., number of fire-year time steps since death) from the resulting snag population would then have an expected value of $1/p_{snags}$ or

the 15.2 five-year time steps (75.8 years). As expected, the mean number of years since death for logs was larger (84.5 years).

Presettlement forest structure

Presettlement forest structure for live and dead trees is summarized in Table 3.3 (plots arranged by increasing number of live trees ha^{-1}). Averages for live trees across all plots were as follows: trees ha^{-1}: 81.7 (s = 27.8), dbh: 43.8 cm (s = 4.1), and stand basal area: 14.1 (s = 3.2) m^2 ha^{-1}. Combining dead structures: 1.6 (s = 1.1) snags ha^{-1}, and 3.1 (s = 3.1) logs ha^{-1}, resulted in a reconstructed mean of 4.7 dead structures ha^{-1}.

The reconstructed partial diameter distributions (for live ponderosa pine trees with dbh ≥ 9.14 cm) at the time prior to fire exclusion (Fig. 3.3) varied in shape, but generally displayed either a unimodal (S1B, S1A, S4B, S5B2) or irregular inverse J-shaped (S4A, S5B3) size distribution (Schubert 1974, Harrington 1982) with as many a three dominant size cohorts. The sensitivity analysis, which assessed assigning death dates at random, showed that reconstructed diameter distributions in 1873-1874 were robust (Fig. 3.3 – error bars) and live tree density varied by no more than 0.5 tree ha^{-1} across all sites. Sensitivity analysis also revealed that the reconstructed estimates of stand basal area were most sensitive to the growth model of S4B and S4B, where estimates were found to vary as much as 2.5% ($\approx$1 m ha^{-1}). As expected, precision in reconstructed diameter distributions decreased as tree density increased and was lowest in the 40-50 cm dbh classes. Plots S5B2 and S5B3, the plots with the smallest extent (1.21 ha), were generally most sensitive to assigning death dates at random and appeared to be most sensitive in the 30-50 cm dbh classes.

Data suggest reference conditions for presettlement snag densities ranged from 0.3 (S1B) to 2.9 (*S5B2*) snags ha^{-1}, were highly variable, and exhibited a tendency for higher snag densities on cinder soil sites (S4A and S4B). The maximum dead tree (snags and logs) density observed was 11 dead trees ha^{-1} on plot *S5B3*. Presettlement log densities consistently increased with live tree densities and ranged from 1.2 (*S4B*) to 9.4 (*S5B3*) trees ha^{-1}. Average reconstructed dbh of both snags and downed trees were larger than the average reconstructed live tree dbh, with the increase in size being as much as 26 cm (*S1B*)

Discussion

The unique historical permanent plots used in this study yielded precise structural reference conditions for southwestern ponderosa pine, utilizing reconstructions over a relatively short period time (< 40 years) with few assumptions. I used these unique sources of information (historical ledgers and stem-maps) to develop a reconstruction model and reconstruct these stands at a time prior to the activities associated with Euro-American settlement (harvesting, grazing, fire exclusion). These reconstructed forest structural conditions using historical permanent plot data may, in turn, be used to validate commonly used dendrochronological reconstruction techniques, serve as baseline for comparisons of contemporary conditions, and provide guidance in determining forest structural restoration objectives.

Presettlement forest structure

Plots S4A and S5B3 were the only sites that exhibited the reverse-J diameter distribution (Nyland 1996) characteristic of balanced, uneven-aged stands, which is the structure most commonly associated with presettlement ponderosa pine forest (Pearson 1950, Schubert 1974, Rietveld 1978, Savage 1991, Bailey and Covington 2002). This result was expected for S4A since this plot was located on cinder soils that cause harsh site conditions for seedlings, yet tends to preserve adequate growing space and often support multiple size classes (O'Hara 1998) while consistently having low live tree mortality rates (Krauch 1930, 1933, Pearson 1939). The size distributions of the remaining plots are best characterized as unimodal even though they are likely uneven-aged and resulted from a gap-type disturbance (Cooper 1960, 1961, Biswell 1961, White 1985, Fulé et al. 2002). Of course, without corresponding age data (e.g., Mast et al. 1999) all inferences of age distribution shape are speculative, however they are supported by studies of the nearby GPNA site (White 1985, Mast et al. 1999).

In the gap model, seedling pulses establish in small forest openings (Cooper 1960, 1961; White 1985, Stephens and Fry 2005, Sánchez Meador et al. *in review*) and were likely thinned by frequent surface fires (Biswell et al. 1973, White 1985). Also, based on the seedling and sapling densities reported in the literature (Savage 1991, Bailey and Covington 2002, Waltz et al. 2003), it seems improbable that densities needed to produce a balanced uneven-aged diameter distribution (over 50 additional trees ha^{-1} in the 0-30 cm classes) could have become established under the presettlement frequent fire regime (White 1985, Fulé et al. 1997, Mast et al. 1999). In addition, there is no reason to believe that smaller trees ($\leq$9.14 cm) would have experienced lower mortality rates prior to fire

exclusion than that observed under contemporary conditions, especially in light of the remarkable persistence of small trees in the absence of fire as reported in the literature (Schubert 1974, Avery et al. 1976, Ronco et al. 1985, White 1985, Moore et al. 2004).

I provided estimates of presettlement densities and sizes of large woody debris such as snags and logs because researchers precisely recorded and mapped these structures in the early 1900s, enabling me to relocate and reconstruct these structures. While presettlement snag densities were highly variable and generally small in number, their importance has been well documented. Large woody debris like snags and logs are known to be of considerable importance for wildlife habitat (Balda 1975, Scott and Patton 1975, Maser et al. 1979, Raphael and White 1984, Laudenslayer 1997; Bate et al., 1999; Chambers and Mast 2005), nutrient cycling and carbon dynamics in forest ecosystems (Harvey et al. 1981, Maser and Trappe 1984, Harmon et al. 1986, Hart 1999), and for their influence on fire behavior and insect outbreaks (Maser et al. 1979, Spies et al. 1988, Covington and Moore 1994a, 1994b). While based on small a sample size (n = 6) mean time since death for snags was found to be similar to that reported by Waskiewicz et al. (*in press*) for clean bark snags (69 years) and log densities were shown to increase with stand density, reflecting a similar association observed today (Moore et al. 2004).

Comparisons to other reconstruction studies

I compared my forest reconstruction structure data to other studies that used dendrochronological reconstructions of contemporary data and found that the two techniques compared favorably. The estimated average presettlement pine densities on

the historical plots had a wide range from 47-125 trees ha^{-1}, while Covington and Moore (1994a) found an average of 43 pines ha^{-1} at Bar-M Canyon, Mast et al. (1999) reported 61 pines ha^{-1} at GPNA, and Waltz et al. (2003) found 62 pines ha^{-1} in the Grand Canyon National Park. The 66 pines ha^{-1} reported (Fulé et al. 1997) as presettlement pine density for the Camp Navajo Army Depot site (Bellmont, AZ) was also within the range reported in this study. It is important to note that the Fulé et al. (1997) study was conducted within a pine-Gambel oak forest having a total presettlement density of 149 trees ha^{-1}, including an additional 80 trees ha^{-1} of Gambel oak (*Quercus gambelii*), 3 trees ha^{-1} of juniper (*Juniperus* spp.), and 1 tree ha^{-1} of white fir (*Abies concolor*).

Presettlement forest structure for my study area also fell within the range of 40 to 255 pines ha^{-1} reported in several early National Forest inventories and other studies in the region (see Table 3.1 for comparisons). In particular, Woolsey (1911) reported a mean of 40 pines ≥ 15.24 cm dbh per hectare on "average" stands in timber-sale areas on the Coconino National Forest and a mean density of 86 pines ≥ 9.14 cm dbh per hectare on "maximum" stands, which was slightly higher than the 81 trees ha^{-1} ≥ 9.14 cm dbh presented in this study. There is no evidence in the reconstructed forest structure data that dense stands existed for this study area: the maximum presettlement tree density was 126.3 trees ha^{-1} (*S5B3*), which is less than 25% of the mean contemporary tree density of 514 trees ha^{-1} reported by Moore et al. (2004). While these values of tree density reported in historical inventories are invaluable for understanding changes that have taken place since Euro-American settlement, they should be interpreted and applied cautiously as they were all conducted after the onset of fire exclusion and intensive livestock grazing.

Only a few historical surveys report snag data in ponderosa pine forests, quantified as percentages of either volume (Lang and Stewart 1910) or total tree density (Leiberg et al. 1904) and none report downed tree reference conditions. Although Mast et al. (1999) sampled dead structures in their dendrochronological study, problems with determining death dates due to decayed sapwood prevented determination of whether the structures were alive or dead before Euro-American settlement. My 1873-1874 reconstructions of dead tree structures were slightly lower than those reported by Mast et al. (1999), but my maximum estimate of total presettlement dead trees (snags and logs combined) of 11 dead trees ha^{-1} for S5B3 was similar to the 13 dead trees ha^{-1} reported by Mast et al. (1999) for their GPNA site.

Management Implications

Managing and sustaining highly altered ecosystems are major challenges for land managers responsible for southwestern ponderosa pine forests. In north-central Arizona, recent forest management projects have focused on the reduction of hazardous fuels and the improvement and conservation of wildlife habitat, with forest structural restoration being of lesser concern. Historical forest inventories and dendrochronological reconstructions provide a range of quantitative estimates of presettlement forest structural conditions that are meant to serve as a basis for ecosystem management and as guides when planning restoration goals.

Dendrochronological reconstruction methods have been shown to produce robust estimates of presettlement density and trees size (Fulé et al. 1997, Huffman et al. 2000). My results also indicated that estimates derived from these types of studies (where

historical data is not available) are indeed robust and useful to managers in determining forest structure and fire regime reference conditions. Land managers must realize that structural reference conditions presented in this study were identified for limited portions of the landscape using a limited sample size, and may deviate on sites of different soils, parent material, and historical conditions. In a forest management context, reference conditions serve as a foundation, or reference point, by which trade-offs of additional management objectives should be evaluated and/or selected, rather than as a rigid target that defines the acceptable outcome of a restoration project (Kauffman et al. 1994, Landres et al. 1999, Moore et al. 1999, Allen et al. 2002). Contemporary ponderosa pine forests of north-central Arizona vary greatly from their presettlement counterparts as well as across the landscape and over time, and restoration plans aimed at achieving desired conditions should vary accordingly. Therefore, strict interpretation and application of reference conditions should be avoided, allowing for the incorporation of additional management objectives or known mechanisms of change, such as climate.

Climate change is known to be an important factor influencing forest change (Shafer et al. 2001) and likely interacts with numerous disturbance (e.g., fire exclusion) effects. While the past influences of climate are not well understood, future climatic conditions are expected to continue having negative effects given current forest conditions (Cocke et al. 2005). Although increases in temperature will likely cause lower altitudes to become too dry to support some species (Shafer et al. 2001), thus possibly negating the suitability of reference conditions, forest conditions presented in this study are consistent with expected trends in climate change. That is, as forests become drier and more likely to burn resulting from increased global temperatures, increased drought, and longer fire

seasons (Hanson and Weltzin 2000; Flannigan et al. 2000), the need to restore more resilient forest structural conditions will only increase in importance.

Based on contemporary ponderosa pine forest conditions, reference conditions reconstructed from historically stem-mapped permanent plots and dendrochronological techniques suggest that structural restoration objectives should emphasize: (1) conservation and retention of all presettlement (> 130 years) trees, as these trees are the main missing component in contemporary forests structure; (2) reducing tree densities with the restoration objective of 50-150 trees ha^{-1} where the corresponding large tree component is 50-25% of the total trees ha^{-1}, respectively; (3) manipulation of the diameter distribution to achieve an unimodal or irregular, uneven-aged shape (possibly targeting a balanced, uneven-aged shape on cinder soils types) through the use of harvest and thinning which mimic gap disturbances (i.e., individual tree selection system); and (4) 3 to 11 structures ha^{-1} (snags and logs) resulting from natural mortality with appropriate increases in snag and log densities where live tree densities increase. In addition, restoration projects should utilize ecosystem management principles and consider long-term (over multiple decades) assessment of success, as many ponderosa pine sites currently do not support the structure to achieve success in the short-term (less than a decade).

While model results should always be applied cautiously, restoration projects should utilize model projections of tree growth and stand dynamics to assist in determining appropriate temporal and spatial scales and to design management plans accordingly. Even though the locations of these plots were not randomly selected, are of a relatively small sample size, and only represent 10% of the Coconino National Forests based on

combined soils (Miller et al. 1995), there is evidence (Moore et al. 2000, Bell 2005) to support that these permanent plots were historically representative of more (at least 17%) of the presettlement ponderosa pine type present on the Coconino National Forest.

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Table 3.1. Historical forest structural characteristics of ponderosa pine forest of north-central Arizona arranged by line of evidence and publication date.

Lines of evidence	Study site	Reference date	Area sampled (ha)	Basal area (m^2 ha^{-1})	Trees ha^{-1}	Average diameter (cm)	dbh distribution reported?	Source
Historical forest surveys and inventories								
	San Francisco Mountains Reserve [a]	1903	202.0	NR [j]	NR	40.6-50.8 dbh	No	Leiberg et al. 1904
	Kaibab National Forest (N.F.) [b, e]	1909	NR	13.6 (14.5)	158 (293)	33.2 QMD	Yes	Lang and Stewart 1910
	Maximum Stand, Coconino N.F. [b, c]	1910	4.1	18.7	86	52.8 QMD	Yes	Woolsey 1911
	Average Stand, Coconino N.F. [d]	1910	NR	8.7	40	53.0 QMD	Yes	Woolsey 1911
	Apache-Sitgreaves N.F. [d, e]	1912	NR	8.5 (19.7)	66 (170)	40.6 QMD	Yes	Greenamyre 1913
	Gus Pearson natural Area (GPNA), Coconino N.F. [d]	1925	64.8	13.3	75	48.5 QMD	Yes	Pearson 1950
	Malay Gap Site, Apache-Sitgreaves N.F. [d, f]	1952	10.9	16.1	255	28.3 QMD	Yes	Cooper 1960
Contemporary forest reconstructions								
	Ft. Valley, Coconino N.F. [g]	1875	7.3	NR	37	NR	No	White 1985
	Bar-M Canyon, Coconino N.F. [h]	1867	17.5	NR	43	NR	No	Covington and Moore 1994a
	North Kaibab R.D., Kaibab N.F. [h]	1881	11.5	NR	23	NR	No	Covington and Moore 1994b
	GPNA, Coconino N.F. [h]	1876	4.7	14.0	12	51.0 QMD	Yes	Covington et al. 1997
	Camp Navajo, Bellemont, AZ [e, i]	1883	24.8	11.7 (12.9)	66 (148)	41.6 QMD	Yes	Fulé et al. 1997
	GPNA, Coconino N.F. [d]	1920	29.0	NR	106	36.4 dbh	No	Biondi 1994
	GPNA, Coconino N.F. [d, h]	1876	4.7	NR	61	NR	No	Mast et al. 1999
	Grand Canyon-Parashant National Monument [e, h]	1870	16.0-40.0	4.6-13.8	62	NR	Yes	Waltz et al. 2003
This study								
	Coconino N.F. [d]	1873-74	15.5	9.2-18.0	45-127	41.5 -51.3 QMD	Yes	

[a] Values summarized and reported by Township and Range
[b] dbh distribution > 15.24 cm
[c] Possible bias due to sampling selection procedures
[d] dbh distribution ≥9.14 cm
[e] Mixed stands: Values in parentheses are for all species.
[f] A value of 784.5 TPH often cited from this source is actually for trees ≤35.56 cm dbh
[g] Values based on live trees (268) with center dates prior to 1876
[h] Values include estimates derived from dead material but no corrections for decomposition
[i] Values include estimates derived from dead material present at time of study
[j] NR: Not Reported

Table 3.2. Model site and growth-period specificity, parameters, and fit statistics for regression models developed and used to reconstruct trees ≥9.14 cm diameter (dbh) on historical plots in 1873-1874. Model form: $Y = b_0 + b_1x + b_2x^2$

Model	Site and growth-period specificity	Y	x_{year}	b_0	b_1	b_2	r^2	SE_{resid}[d]	n
Tree dbh-dss allometric relationship									
	All sites	dbh	dss_{2002}	0.2374[a]	0.8830	0	0.9651	1.1819	192
Tree size and previous basal area growth increment relationships									
	S1A & S1B (post-harvest)		dbh_{1909}	-10.0900	0.1785	-0.0020[b]	0.4075	0.4437	54
	S1A & S1B (pre-harvest)	BA increment[e]	dbh_{1894}	-9.0253	0.1074	-0.0012[c]	0.2146	0.5832	54
	S4A & S4B (pre-harvest)		dbh_{1909}	-9.3685	0.1180	-0.0011[c]	0.5139	0.3458	69
	S5B2 & S5B3 (pre-harvest)		dbh_{1913}	-10.6800	0.1726	-0.0016[b]	0.3048	0.8297	46

[a]: Not significant
[b]: significant at the $\alpha \leq 0.001$ level
[c]: significant at the $0.001 < \alpha \leq 0.01$ level
[d]: estimated standard error of the residuals
[e]: For the previous 5-year period in m^2

Table 3.3. Reconstructed stand attributes (live ponderosa pine trees with dbh ≥ 9.14 cm) of six permanent plots located on the Coconino National Forest, Arizona in 1873-1874, arranged by increasing live tree density. Observed values are the average values of each stand attribute over 100 simulations of the reconstruction model.

	Site					
	S1B	*S4B*	*S4A*	*S1A*	*S5B2*	*S5B3*
	Live trees					
Density (trees ha^{-1})	44.27	66.75	79.51	76.98	96.33	126.26
Plot Size (ha)	4.05	3.24	3.24	2.59	1.21	1.21
Mean dbh ± s[a] (cm)	48.15 ± 17.69	46.44 ± 20.36	40.76 ± 22.04	43.56 ± 19.02	46.65 ± 14.49	37.42 ± 17.91
Minimum dbh (cm)	9.55	9.80	9.44	10.22	10.21	9.60
Maximum dbh (cm)	103.97	114.15	96.43	104.13	90.52	97.98
QMD (cm)	51.29	50.69	46.32	47.51	48.83	41.46
BA (m^2 ha^{-1})	9.15	13.47	13.40	13.65	18.04	17.05
Site Index (m)	16.7	18.8	17.6	16.4	15.8	14.6
	Snags					
Density (trees ha^{-1})	0.31	2.44	2.24	1.12	2.93	0.70
BA (m^2 ha^{-1})	0.15	1.05	0.63	0.25	0.75	0.22
Mean dbh ± s (cm)	74.17 ± 32.80	69.43 ± 26.43	56.28 ± 20.02	51.68 ± 11.00	55.70 ± 11.97	63.46 ± 3.54
QMD (cm)	79.43	73.87	59.77	52.70	57.06	63.52
	Logs					
Density (trees ha^{-1})	1.65	1.18	1.89	2.03	2.39	9.40
BA (m^2 ha^{-1})	0.75	0.21	0.54	0.40	0.52	2.15
Mean dbh ± s (cm)	73.60 ± 19.45	47.33 ± 7.59	58.77 ± 12.33	44.18 ± 24.97	51.82 ± 6.91	51.27 ± 17.31
QMD (cm)	76.01	47.72	60.06	50.27	52.46	54.02

[a]: s = standard deviation

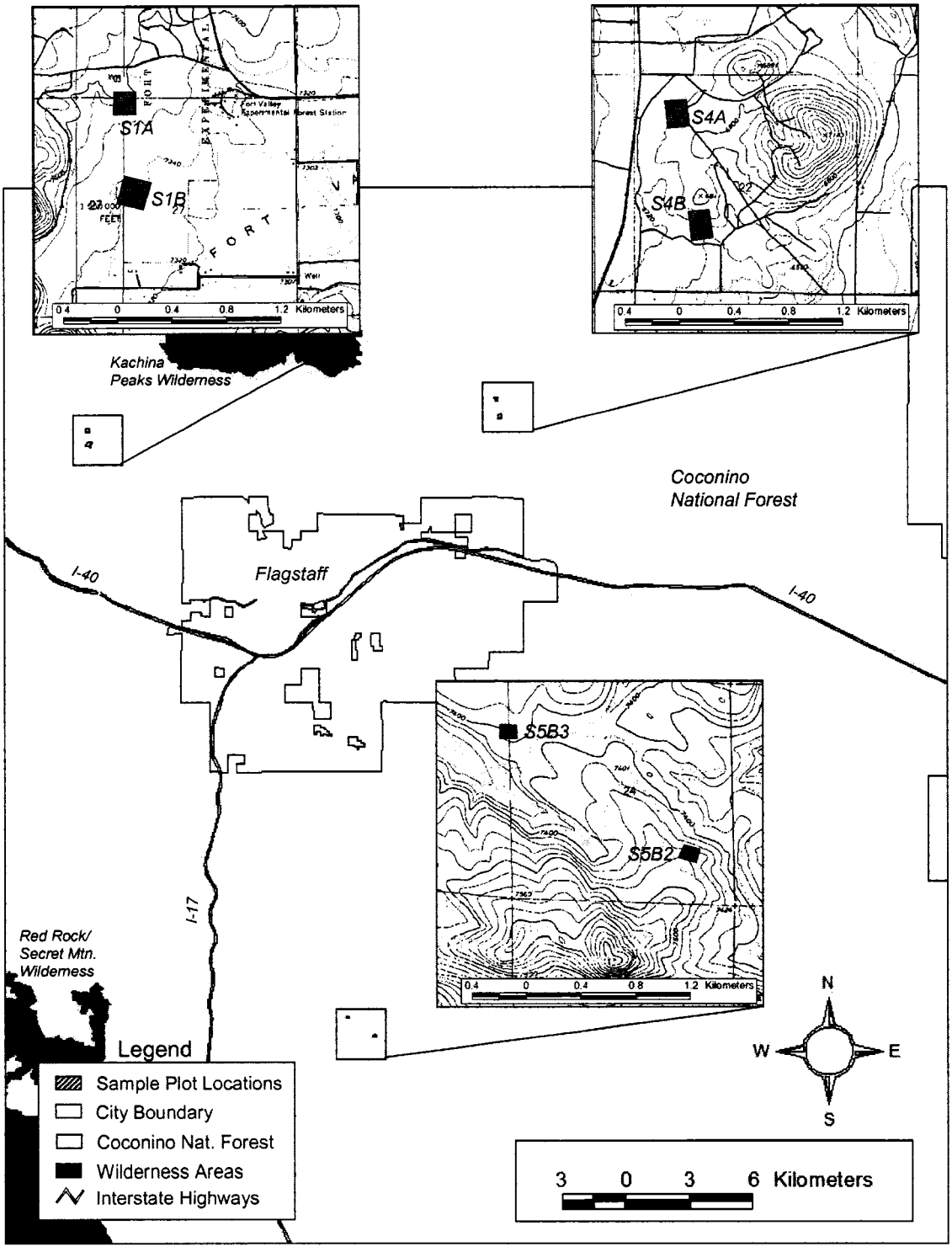

Figure 3.1. Location of the historical ponderosa pine permanent plots examined within the Coconino National Forest near Flagstaff, Arizona.

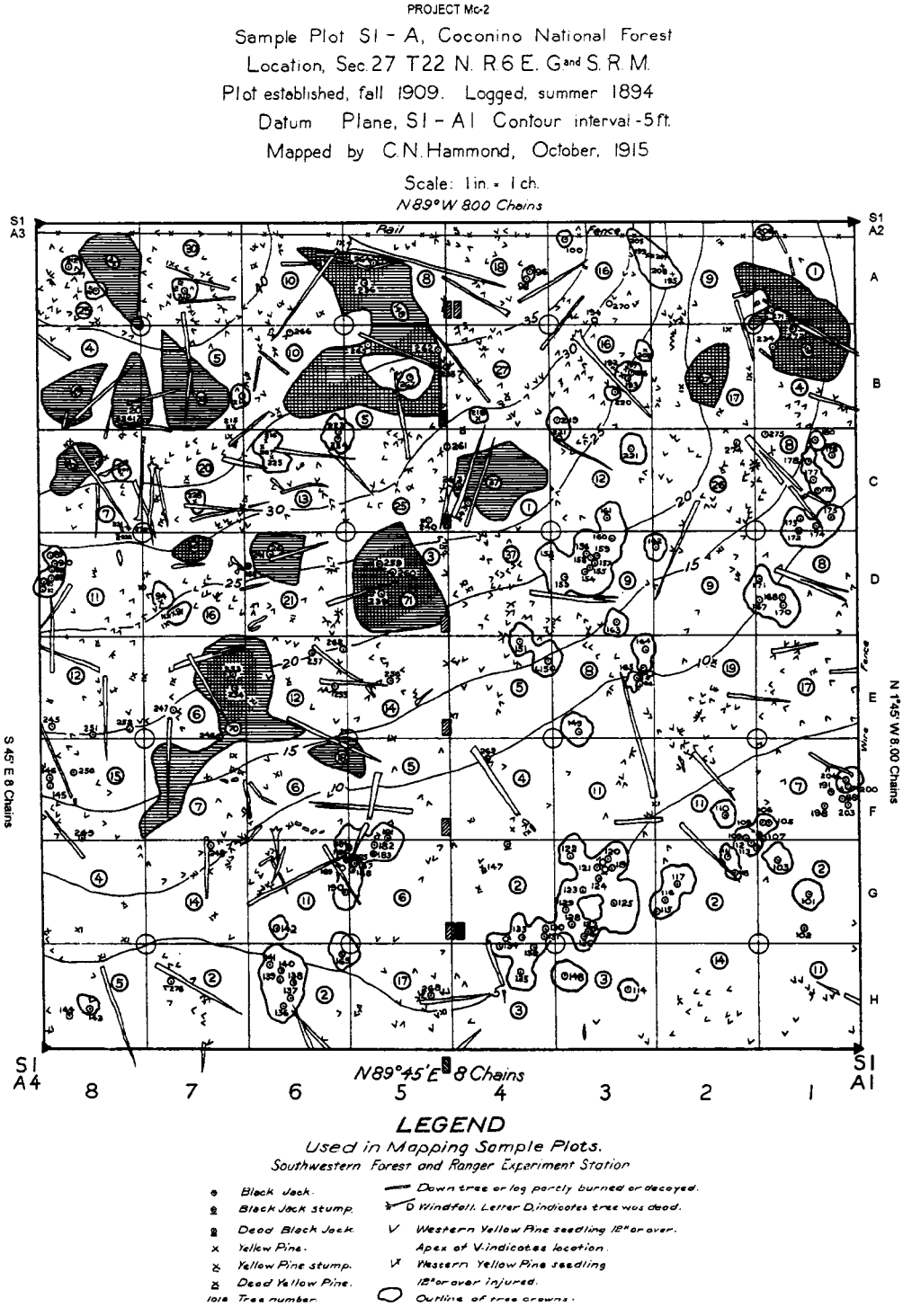

Figure 3.2. Example stem map (data originally collected in 1909; map created in 1915) of plot COCS1A showing locations of live trees ≥ 9.14 cm dbh, stumps and logging debris from 1894 harvest activity, standing snags, logs, and other structures present on the plot at the time of establishment. Legend terms defined in Moore et al. (2004). *Redrawn with permission).*

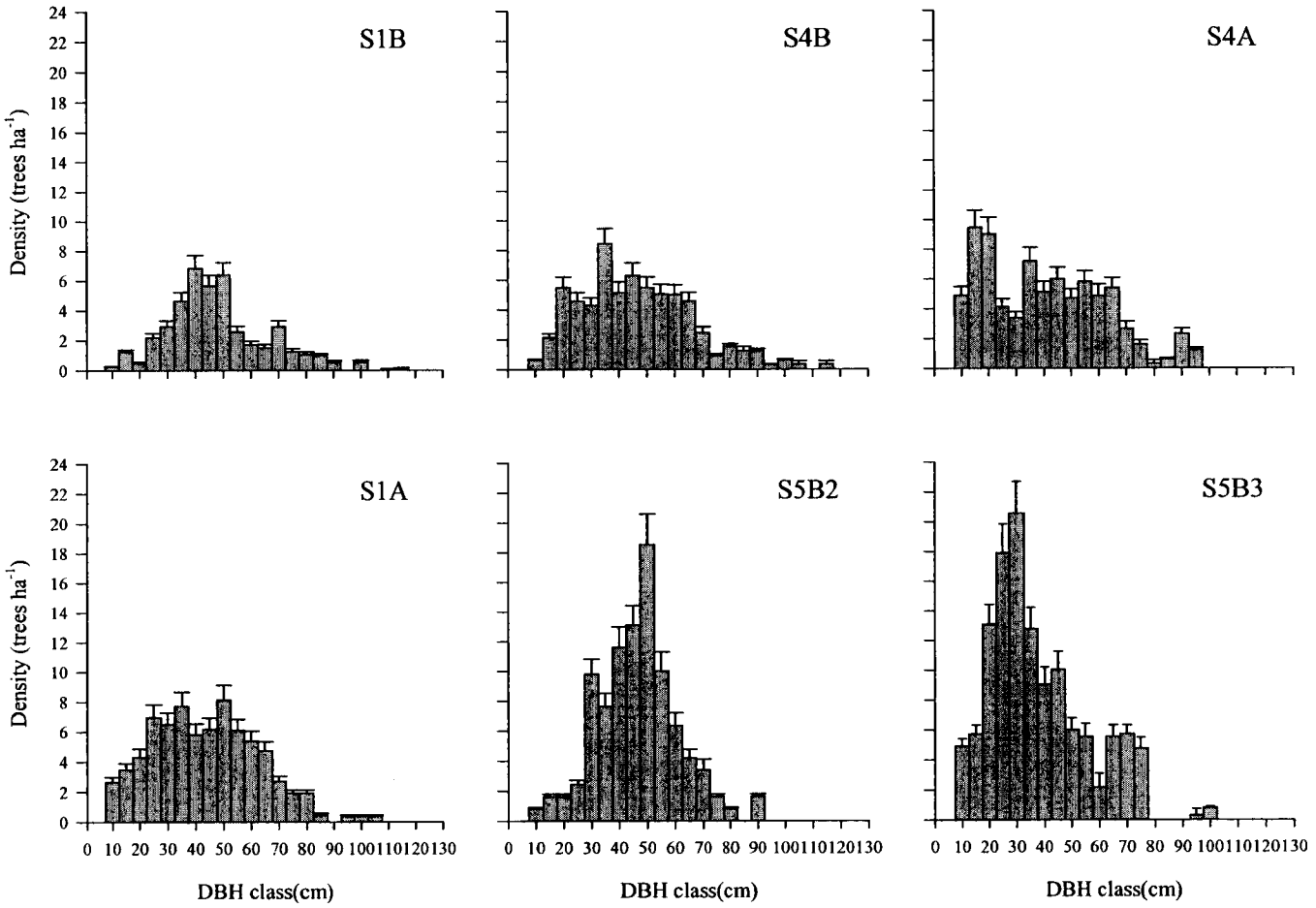

Figure 3.3. Reconstructed (1873-1874) partial diameter (live ponderosa pine trees with dbh ≥ 9.14 cm) distributions in 5 cm classes of the six permanent plots located on the Coconino National Forest, Arizona, arranged by increasing live tree density. Observed values are the average mean (vertical bars) and standard deviation (error bars) over 100 simulations of the reconstruction model.

Chapter 4

A New Method for Determining Spatial Reference Conditions in Ponderosa Pine Forests of North-Central Arizona

Abstract

Descriptions of stand structure in southwestern ponderosa pine forest have tended to focus on stand-level collective attributes such as tree density and basal area. Although these forests are known to exhibit a patchy arrangement of trees, little attention has been given to quantifying the spatial patterns of either patches or the individual trees within and among patches. I propose a new method for delineating patches and quantify the spatial pattern of patches and trees prior to Euro-American settlement on six plots near Flagstaff, AZ. The patch delineation method proposed here allowed me to conduct between- and within-patch, as well as stand-level analysis of spatial patterns. Presettlement ponderosa pine trees were aggregated in patches ranging in size from 0.01 ha to 0.15 ha prior to Euro-American settlement. Presettlement patch densities ranged from 10 to 27 patches ha^{-1}, which accounted for 62% to 75% of the stand basal area (m^2 ha^{-1}) and exhibited highly variable tree diameters both between multiple patches and within a single patch. I compared the spatial pattern of reconstructed presettlement reference conditions with spatial pattern descriptions presented in the literature for ponderosa pine forests of north-central Arizona and recommend management strategies emphasizing stand- and patch-level patterns.

Introduction

The spatial pattern of forests has been shown to influence tree growth (Ronco et al. 1985, Ffolliott et al. 2000), plant species diversity (Laughlin et al. *in press)*, wildlife habitat (Patton 1977, Graham et al. 1994, Meyer and Sisk 2001, Waltz and Covington 2003), and population dynamics (Addicott et al. 1987). Although it is known that southwestern ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum*) stand conditions prior to Euro-American settlement of north-central Arizona (circa 1876 [Dieterich 1980]), or presettlement stand conditions, displayed a patchy (grouped) arrangement of trees (Pearson 1923, Schubert 1974, Cooper 1960, 1961, White 1985), little attention has been given to quantifying the spatial patterns of either patches or the individual trees within and among those tree groups.

The majority of stand structural descriptions presented in the literature have focused on stand-level collective attributes such as tree density, basal area, and mean size. However, the issue of spatial patterns has played a major role in southwestern ponderosa pine forest management, since Reynolds et al.'s (1992) recommendations for northern Goshawk (*Accipiter gentilis)* habitat (which focus on patches) were widely adopted by the United States Forest Service as amendments to Forest Plans throughout Region 3 (Arizona and New Mexico, USFS 1996). These recommendations, known as the "Goshawk Guidelines", are based on proportioning the landscape into each of six vegetation structural or growth stages (ranging from opening to old forest conditions) and specifically recommends patches (or clumps) of large live trees with interlocking crowns as foraging habitat. However, the study by Reynolds et al. (1992) made no attempt to

define the concept of "patch" and focused on surveys of post-settlement tree size and canopy cover, which have been shown to be outside of the natural range of ponderosa pine forests (Moore et al. 2004).

Spatial statistics and analyses can provide quantitative descriptions of spatial patterns and give insight into the scale at which historical and environmental processes influence stand dynamics (Youngblood et al. 2004, Boyden et al. 2005, Fortin and Dale 2005). Knowledge of spatial patterns, combined with conventional descriptions of stand structure, can help guide the development of silvicultural practices and forest management strategies to better suit the wide range of objectives applied in southwestern ponderosa pine forests. Until recently, spatial information was usually derived from casual observations and subjective delineations of patches and openings.

In the White Mountains of Arizona, Cooper (1960, 1961) outlined four scales of pattern in ponderosa pine forests: (1) landscape-level, caused by local variations in elevation, topography, and parent material, (2) stand-level, resulting from the mosaic of patches, (3) between-patch, and (4) within-patch (or between-tree). Cooper further suggested that even-aged patches (inferred entirely from tree size) tended to develop on favorable seedbeds or "safe-sites" (sensu Harper 1977), which arose from isolated high-intensity fire events that burned entire dead patches. In a more recent study focused on exploring the validity of Cooper's even-aged-patch hypothesis, White (1985) determined that the Gus Pearson Natural Area (GPNA) near Flagstaff, Arizona was instead composed of a mosaic of mixed-sized, uneven-aged groups (called patches hereafter). Contrary to Cooper, White hypothesized that seedlings established on "safe-sites" created not by entire-patch mortality events but rather by individual-tree mortality.

Both of those studies focused on quantifying the stand-level pattern associated with the mosaic of small patches. Cooper (1961) tested spatial pattern using nearest neighbor analysis (Clark and Evans 1954) and found stands to be aggregated. He then used the contiguous quadrat method (Grieg-Smith 1952) to infer that patch sizes ranged between 0.06 - 0.14 ha, but made no attempt to either define/delineate patches or explore fine-scale patterns. On the other hand, White (1985) focused almost exclusively on patches, which he defined as "three or more trees" and delineated using an indirect method. He used the area of influence of the prolific 1919 cohort observed at the Gus Pearson Natural Area (Savage et al. 1996) to delineate the area of influence for old trees (i.e., delineated old tree patches by delineating post-settlement establishment) and reported patch sizes ranging between 0.02 - 0.29 ha. White's method, while easily implemented, is highly subjective and obviously not applicable on sites where a differentiation of age classes or populations is unclear.

More recently, Lang (1994) utilized spatial point pattern analysis to assess patches and spatial structure surrounding northern Goshawk nest sites and that of "old-growth" sites in the White Mountains of east-central Arizona. Although spatial point pattern analysis has been commonly applied to examine tree spatial patterns (e.g., Getis and Franklin 1987, Moeur 1993, Fulé and Covington 1998, Mast and Veblen 1999, Youngblood et al. 2004, Boyden et al. 2005), it has no provision for delineating patches. To do so, Lang first defined a patch as "two or more connected crown projections", and then delineated patches by predicting crown diameter from individual tree DBH and examined the resulting patch structures having two or more interconnected crowns.

Using this method, Lang found patches averaged 0.002 ha in size but reported no measure of variability.

Previous studies of spatial patterns provide valuable insight into the range of conditions exhibited by Arizona ponderosa pine forests in a "natural" or "old-growth" context. However, their descriptions are either incomplete or subjective and do not portray 'reference' spatial patterns; therefore they should be interpreted and applied cautiously.

The objectives of this study were to: a) use point pattern analysis to determine if the spatial distribution of trees was random, aggregated, or uniform, and b) to propose a new method for delineating patches aimed at facilitating forest spatial pattern analyses. As a case study, I used reconstructed presettlement reference conditions (1873-1874) on six permanent plots in the ponderosa pine forest type near Flagstaff, Arizona (Chapter 2) to evaluate stand-, between-patch-, and within-patch-level patterns; and as a base datum for comparison with the forest spatial patterns reported by Cooper (1961), White (1985) and Lang (1994).

Methods

Project history and study sites

I focused on the spatial patterns of six reconstructed permanent plots composed almost exclusively of ponderosa pine on the Coconino National Forest near Flagstaff, Arizona. I sampled two plots at each of three sites in the ponderosa pie forest type, which are located 10 km northwest (plots denoted as S1A and S1B), 15 km northeast (S4A and S4B), and 21 km south (S5B2 and S5B3) of Flagstaff (see Fig. 3.1, Chapter 3).

Briefly, the plots ranged in size from 1.21 to 4.05 ha, were located at elevations between 2050 and 2250 m, and represent roughly 7% of the ponderosa pine type of the Coconino National Forest based on soil types (see Chapter 3). Historical and contemporary field methods, as well as contemporary conditions, are detailed by Moore et al. (2004), who report on stand structural changes within a 1-ha subplot on these (excluding S5B2) and other permanent plots throughout Arizona and New Mexico.

For this study, I measured all live and dead tree structures including stumps, snags, and windfallen trees that grew to at least breast height (1.37 m) on each plot at its original extent (1.21 - 4.05 ha). I located all tree structures using historical stem-maps (Chapter 3, Fig. 3.2) and measured spatial coordinates to the nearest 0.1 meter and 0.1 degree using the Impulse 400 laser rangefinder and MapStar compass system, manufactured by Laser Technology Inc.

Stand-level patterns

I used point pattern analysis to determine if the spatial distribution of trees was random (also called complete spatial randomness or CSR), aggregated, or uniform (Upton and Fingleton 1985, Legendre 1993). Specifically, I used the Ripley's K(t) function (Ripley 1976, 1977, 1981) with a square-root, variance-stabilizing transformation of K(t) to L(t)-t (Besag 1977), to evaluate the spatial pattern at multiple scales. L(t)-t values larger than, equal to, and smaller than 0 indicate aggregated, random, and uniform spatial distributions, respectively. To test for significance, I used a Monte Carlo simulation approach (Upton and Fingleton 1985, Dale 1999) to compare the

resulting L(t)-t values with a frequency distribution from 99 simulated random point patterns.

Patch-level patterns

If the reconstructed stand-level spatial patterns were aggregated, I further described the characteristics of the stand in terms of patch density, proportion of trees in patches, and the patches themselves including patch size, tree density, and basal area. I first estimated patch size by examining the lag distance and value of L(t)-t at the point of maximum divergence from CSR (Reich and Davis 1998, Boyden et al. 2005). This approach produced results that could be directly compared to estimates of patch sizes reported by Cooper (1961), White (1985), and Lang (1994).

To describe between- and within-patch attributes, as well as facilitate comparisons between plots, I also proposed a new method for designating and delineating patches. This method was based on establishing: a) minimum number of trees per patch and b) a maximum (limiting) between-tree distance within patches. As there is no evidence suggesting that two trees function as less of a patch than three trees, I chose to use Lang's (1994) definition of two or more trees to define a patch. I desired a between-tree limiting distance that represented a compromise between management practicalities, issues of scale, and allowed for potential patches or for small individuals to be recruited into existing groups.

First, I computed the between-tree distance (i.e., the sum of two tree radii being considered for patch membership) for all distances up the point at which the stand was all one patch. Next, I assessed the sensitivity of the between-tree distance by examining the

proportion of total trees designated as members of patches. Then, a selection of an individual tree's limiting distance (half of the between-tree limiting distance) was made based on the following criteria: 1) easily marked and measured in the field, 2) required only x-y coordinates and some measure of tree size (e.g., DBH, crown radius, etc.), 3) captured differences in stand structure (e.g., was smaller for dense stands), 4) maximized trade-offs of scale (i.e., did not result in one large patch or patch densities essentially equal to tree densities), and 5) rooted in the concept that crown interconnectivity is an important patch attribute and ultimately delineates a patch's area of influence (White 1985, Lang 1994).

To allow for the assessment of crown radii values as a potential tree limiting distances, predicted values were obtained using the reconstructed DBH values (1873-1874, Chapter 3) and a regression built on data from 5,075 ponderosa pine trees on the Coconino National Forest. The relationship between crown radius and tree DBH is known to be strong (Hitchcock 1974, Hemery et al. 2005) and was modeled using contemporary tree DBH and two measurements of crown radius (taken from the center of the tree stem to the perimeter of the crown along the longest and shortest radii of the crown from) on 18 permanent plots.

This method, combined with projections of patch canopy area, allowed me to produce patches that I compared with those reported by White (1985) and Lang (1994). Using all patches that fell entirely within the plots and thus correcting for edge effects, I examined the range of variability for attributes characterizing structure between-patches (such as patch size, basal area, and tree density), and within-patch (such as tree size and nearest neighbor distance) structure.

Results

Stand-level patterns

As expected, the trees on the reconstructed plots were significantly aggregated on all sites (Fig. 4.1). Trees were most strongly aggregated on S1B (most deviation from CSR) and least aggregated on S5B3. Although trees on all sites were aggregated up to at least 36 m, scales of significant aggregation varied, being at a larger extent than the plot extent for sites S1B, S4A, and S5B3. All sites exhibited single distinct peaks in aggregation except S5B3 and S1B, which appeared to fluctuate between 5-15 m and exhibited a second peak at around 80 m, respectively.

Patch-level patterns

All sites exhibited peaks in aggregation between 6 and 22 m lag distances (Fig. 4.1), corresponding to patches of trees ranging in size from 0.01 ha to 0.15 ha prior to Euro-American settlement.

As expected, the sensitivity analysis (Fig. 4.2) revealed that the proportion of total trees designated as members of patches was positively correlated with between-tree limiting distance. All sites were designated as one large patch when the limiting distance reached 12 m and an asymptote is obvious around 6 m, which corresponded to the maximum crown radius observed in my contemporary dataset.

The resulting equation and fit statistics quantifying the strong positive relationship between crown radius and DBH are presented in Figure 4.3. A power function provided the best fit as judged by the distribution of residuals and a high coefficient of determination ($r^2 = 0.83$). The resulting predicted crown radii were ultimately used to

delineate the area of influence for all reconstructed individual trees. Furthermore, the 3rd quartile crown radius was selected for use as the individual tree limiting distance. Crown radius can be easily quantified using a variety of data sources (field measurements, aerial imagery, etc.), is a measure of tree size and allows for the examination of crown interconnectivity, and is sensitive to differences in stand structure (density, DBH, canopy cover). The 3rd quartile crown radius was also selected because it corresponded with the results of the sensitivity analysis (i.e., it maximized the trade-offs of scale).

Corresponding between-tree limiting distances (sum of the two trees' crown radii) ranged between 5.3 - 6.6 m and produced as few as 10 and as many as 27 patches ha^{-1} (S1B and S5B3, respectively).

The resulting range of variability for between-patch and within-patch attributes is presented in Table 4.1. Trees in patches exhibited less size variability (Table 4.1). The average size of trees on each site ranged from 32.2 to 44.4 cm for trees in patches, and 39.5 to 58.4 cm for trees outside of patches. By definition, the mean distance to the nearest neighboring tree was lower between trees in patches than those not in patches. Patches that fell entirely within the plots S1B and S5B3 are shown in Fig. 4.4a and 4.5a, and their tree DBH density and variability is displayed in Fig. 4.4b and 4.5b, respectively. Patches composed of two to three trees exhibited highly variable tree DBH distributions (e.g., Fig 4.4, patches 5 and 6). For patches of more than three trees, there appeared to be a decreasing trend in median tree size and overall variability as number of trees increased (e.g., Fig 4.4b, patches 27 through 37). Additional figures showing patches and their associated between- and within-patch attributes for all other sites are displayed in the Appendix (Fig. 4.7 - 4.10).

The majority of the individual trees on each site were members of patches (75% to 84% of the total trees ha^{-1}), and these trees accounted for 62% to 75% of the total basal area ($m^2 ha^{-1}$). The resulting average densities ranged from 3.6 to 5.4 trees per patch, the largest being composed of 24 trees (Table 4.1; S4A). The maximum basal area for a patch (2.62 m^2) was observed on S4B for a corresponding patch area of 0.04 ha.

Discussion

Stand-level patterns

Point pattern analysis indicated that an aggregated spatial pattern best described the arrangement of trees across all sites at short distances ($\leq$36 m). That characteristic may likely be attributed to gap dynamics (Watt 1947) in that a patch of seedlings could have established in a gap created by a fallen and burned log, and then were subsequently thinned by fire (White 1985). These results agree with the common interpretation of southwestern ponderosa pine stand development as consisting of episodic tree establishment in uneven-aged groups (White 1985, Mast et al. 1999, Bailey and Covington 2002). Although spatial analysis revealed that the two sites (S1B and S5B3) located next to large grassy expanses, or parks, were aggregated at all spatial scales, a similar pattern was also observed at one of the cinder soil sites (S4A). Therefore, I speculate that spatial aggregation at all scales ($\leq$ 100 m) is to be expected in areas with increased seedling mortality, likely resulting from frost-heaving (Heidmann 1976), periods of extreme drought (Larson and Schubert 1970), and/or increased competition from herbaceous plants for important resources such as soil moisture (Larson and Schubert 1969).

Cooper (1961), White (1985), and Lang (1994) found that ponderosa pine grew in small groups. My results with respect to patch size derived from point pattern analysis are consistent with those studies. These multiple lines of evidence, in conjunction with my reconstructed structural data, frequency of individual-tree mortality events shown on the historical stem-maps (see Chapter 3, Fig. 3.2), and the uneven-age distributions of numerous nearby studies (e.g., White 1985, Fulé et al. 1997, Mast et al. 1999) support the notion that presettlement southwestern ponderosa pine forest near Flagstaff, Arizona were historically composed of a mosaic of small, uneven-aged patches.

Patch-level patterns

Sensitivity analysis revealed that the proportion of trees designated as members of patches was highly sensitive to the between-tree, limiting distance over short distances ($\leq$ 6 m). Even though the number of patches varied with spatial scale, the proportion of total trees and associated basal area in patches varied little, suggesting that some stand-level attributes are not sensitive to the patch designation (between-tree, limiting distance) criterion. Sensitivity analysis also aided in selection of crown radius as the tree limiting distance, which efficiently placed trees into distinct patches.

My within-patch size data indicated highly variable and wide-ranging tree sizes, contrary to Cooper's even-aged hypothesis for ponderosa pine of the White Mountains. Although DBH is known to be a poor surrogate for age in southwestern ponderosa pine, variability in my reconstructed data and the historical stem-maps does not support the presence of even-sized trees within patches nor does it show any events of entire patch mortality.

Another possible explanation for the high degree of between- and within-patch variability is the lack of adequate regeneration sites as suggested by White (1985). Similar to White's 22%, my results of only 11-19% of the study areas being occupied by trees (≥9.14cm DBH) prior to Euro-American settlement also suggested that low frequency of safe sites might have been a limiting factor for regeneration events. However, that premise does not explain how single and paired trees came to occupy the interspaces between patches, as evidenced by the reconstructed conditions. Further investigation is needed to determine if these single and/or paired trees represent the beginning of a new patch, the lone survivors of a dying patch, or something altogether different. Although numerous snags and logs were reconstructed as present prior to Euro-American settlement (average of 5 ha^{-1}, Chapter 3), the majority of such structures seemed to occur around existing patches or as isolated trees (see Chapter 3, Fig. 3.2).

Although the patch designation methods applied in this study are different from those previously used to quantify spatial pattern in ponderosa pine (Cooper 1961, White 1985, Lang 1994), the resulting patch sizes could be compared. My approach was similar to that of White (1985) and Lang (1994) because it assumed that the area occupied by each patch could be defined by its area of influence.

White (1985) used the area of influence of the prolific 1919 cohort observed at the Gus Pearson Natural Area to delineate the area of influence of the old-growth trees, and Lang (1994) used the interconnectivity of projected tree canopies to designate the area of influence for similarly aged trees. White's method was highly subjective and not a valid technique on sites where the 1919 cohort does not dominate (e.g., S1A; see Chapter 2), whereas Lang's method resulted in high patch densities that are likely impractical for

management objectives and field operations. My selection of the 3rd quartile tree diameter to determine the between-tree, limiting distance may also be considered subjective. However, this approach produced relevant practical results by allowing for the detection of subtle differences between sites since it automatically adapts itself to stands of varying number of trees. For example, sites with high number of trees will be characterized by smaller DBH and crown radii. Therefore, the 3rd quartile tree diameter and corresponding limiting distance will be smaller, which would in turn allow between- and within-patch attributes to be detected. This method is also easily replicable in other stands and customizable by practitioners, who could modify the patch-designation criterion by selecting other data characteristics (such as other quartiles, mean, etc.) which are readily-obtainable from any set of DBH data.

Management Implications

Past management activities (i.e., harvesting, livestock grazing, fire exclusion) and the progression of stand dynamics often obscure presettlement tree spatial patterns (Chapter 2). The techniques used in this study required extensive stem-mapping (which is labor intensive) to quantify spatial reference conditions, yet vast amounts of quality data were derived from only a few plots. Using that information to quantify the spatial heterogeneity of past and contemporary forest structure further enables managers to understand not only how ecosystems have been altered but also set management and restoration targets accordingly. Laughlin et al. (2006) found that herbaceous standing crop targets (kg ha^{-1}) after restoration treatments were not met under tree patches and suggested the consideration of increased patch type heterogeneity, including the creation

of openings. Similarly, treatments targeting spatial patterns in the form of a shifting patchwork of tree patches within a relatively open matrix have been recommended when restoration targets of improved invertebrate habitat (Meyers and Sisk 2001) and increased microclimate heterogeneity (Meyer et al. 2001) are deemed important. Currently implemented restoration (thinning) prescriptions, like those outlined by Mast (2003), focus on the preservation of all presettlement trees and often indirectly advocate the retention of the largest post-settlement trees by selecting the largest "leave-trees" within a certain distance of presettlement evidence. The retention of these trees, which commonly established first in the overgrazed grassy interspaces (see Chapter 2), may likely result in a tree spatial patterns very different from those presented in this study. Suggesting the importance of considering tree locations, as well as size or age, when marking restoration prescriptions.

The management of highly-altered ecosystems is a major challenge for land managers. This is true in southwestern ponderosa pine forests of north-central Arizona, which have changed drastically since presettlement times and are known to be patchy in pattern. However, the method proposed in this study allows for the spatial analysis of stand- and patch-level patterns of not only reconstructed presettlement but current conditions as well. Ultimately, information generated by this approach may serve to compare both conditions and establish guidelines to achieve forest management and restoration objectives that incorporate spatial structure.

I recommend that forest management projects in ponderosa pine type of north-central Arizona consider: (1) quantifying current and 'reference' spatial patterns by using a patch-delineation approach such as the one proposed in this study; (2) applying silvicultural treatments that promote presettlement 'reference' spatial patterns shown to be within the historical range of spatial variability.

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Table 4.1. Reconstructed spatial attributes at the stand, patch, and individual tree level arranged by increasing live tree density.

	Site					
	S1B	*S1A*	*S4B*	*S4A*	*S5B2*	*S5B3*
	Stand					
Density (patches ha^{-1})	10	11	11	13	20	27
Percent in patches						
Tree density	74.9	76.4	77.8	81.2	83.8	82.9
Basal area	61.7	67.0	63.5	64.8	74.3	68.9
Percent canopy cover	10.2	15.8	14.1	13.6	16.7	18.8
	Patch					
Mean ± s[a]						
Size (m^2)	70.4 ± 38.5	89.5 ± 52.3	75.3 ± 65.9	59.7 ± 29.2	59.2 ± 45.5	44.5 ± 30.3
Density (Trees patch^{-1})	3.6 ± 3.7	5.4 ± 3.9	4.0 ± 3.9	4.6 ± 4.6	3.8 ± 2.8	3.9 ± 2.8
Basal Area (m^2 patch^{-1})	0.56 ± 0.37	0.72 ± 0.43	0.60 ± 0.50	0.47 ± 0.27	0.47 ± 0.30	0.32 ± 0.22
Maximum						
Size (m^2)	191.3	246.6	368.4	152.2	222.4	134
Density (Trees patch^{-1})	12	19	22	24	14	15
Basal Area (m^2 patch^{-1})	1.42	1.93	2.62	1.22	1.32	1.09
	Individual Tree					
Mean DBH ± s (cm)						
Within Patches	44.4 ± 15.3	41.1 ± 14.9	42.6 ± 12.4	38.4 ± 13.6	39.8 ± 10.89	32.2 ± 10.3
Not in Patches	52 9 ± 18.6	51.8 ± 19.7	58.4 ± 20.6	49.3 ± 22.9	48.5 ± 19.8	39.5 ± 16.3
Mean NND ± s (m)						
Within Patches	3.4 ± 1.6	3.3 ± 1.7	3.1 ± 1.7	3.2 ± 1.29	2.7 ± 1.3	2.3 ± 1.2
Not in Patches	11.1 ± 5.1	10.3 ± 2.5	12.4 ± 4.9	11.0 ± 4.1	9.5 ± 3.8	7.9 ± 3.1

[a] : s = standard deviation

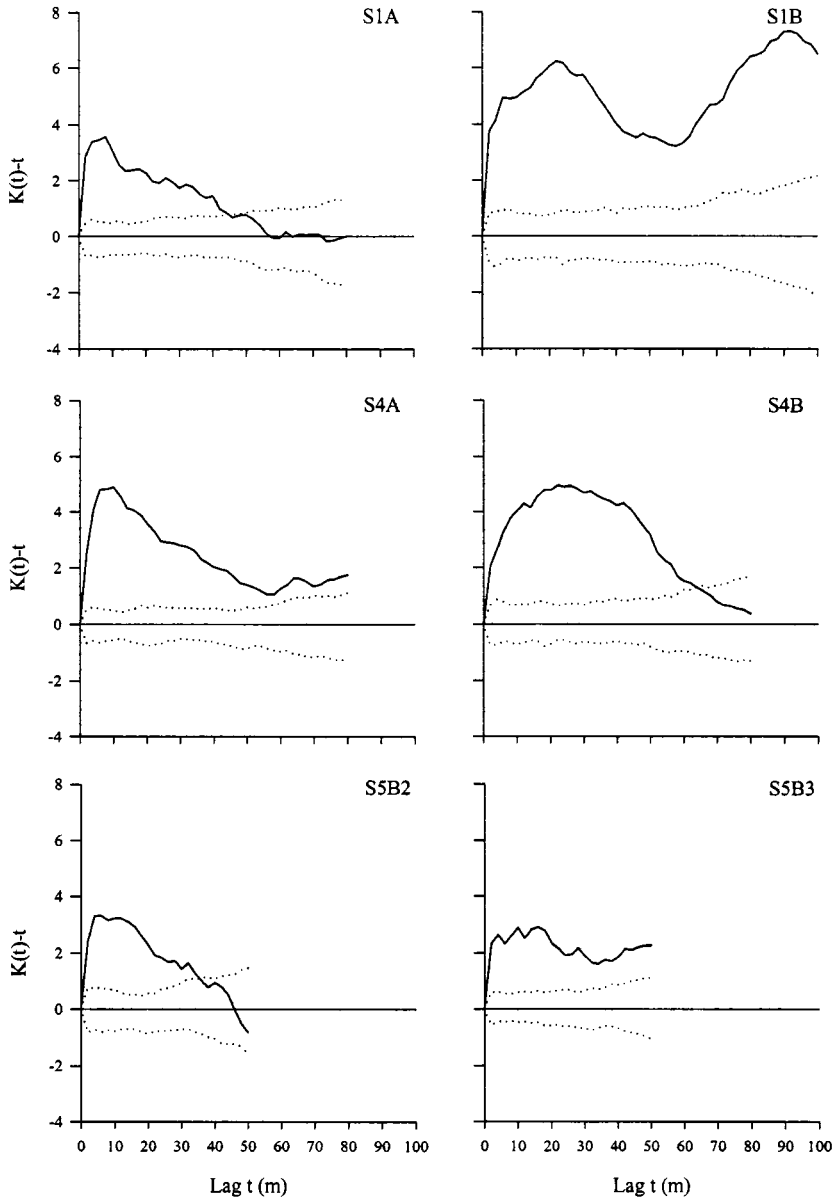

Figure 4.1. Ripley's K(t) univariate statistic (transformed as [L(t)-t]) as a function of lag distance. The horizontal solid line is the expectation under CSR (random) and the dotted lines on either side of it are the 95% confidence limits. Calculated values that fall outside of the confidence interval are statistically significant; values > 0 indicate aggregation and values < 0 indicate uniform (regular) spatial distribution.

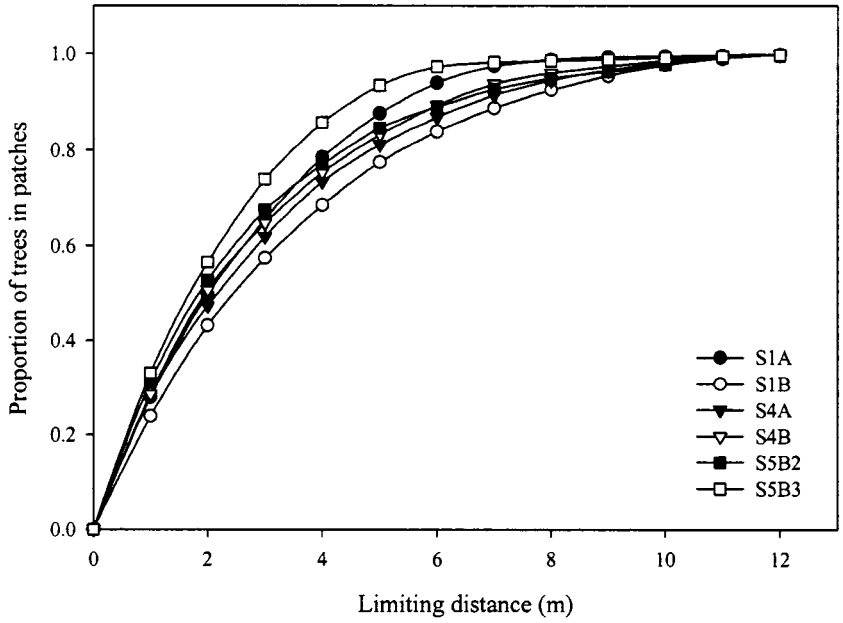

Figure 4.2. Sensitivity of proportion of total trees designated as members of patches to the between-tree limiting distance criterion used in patch selections.

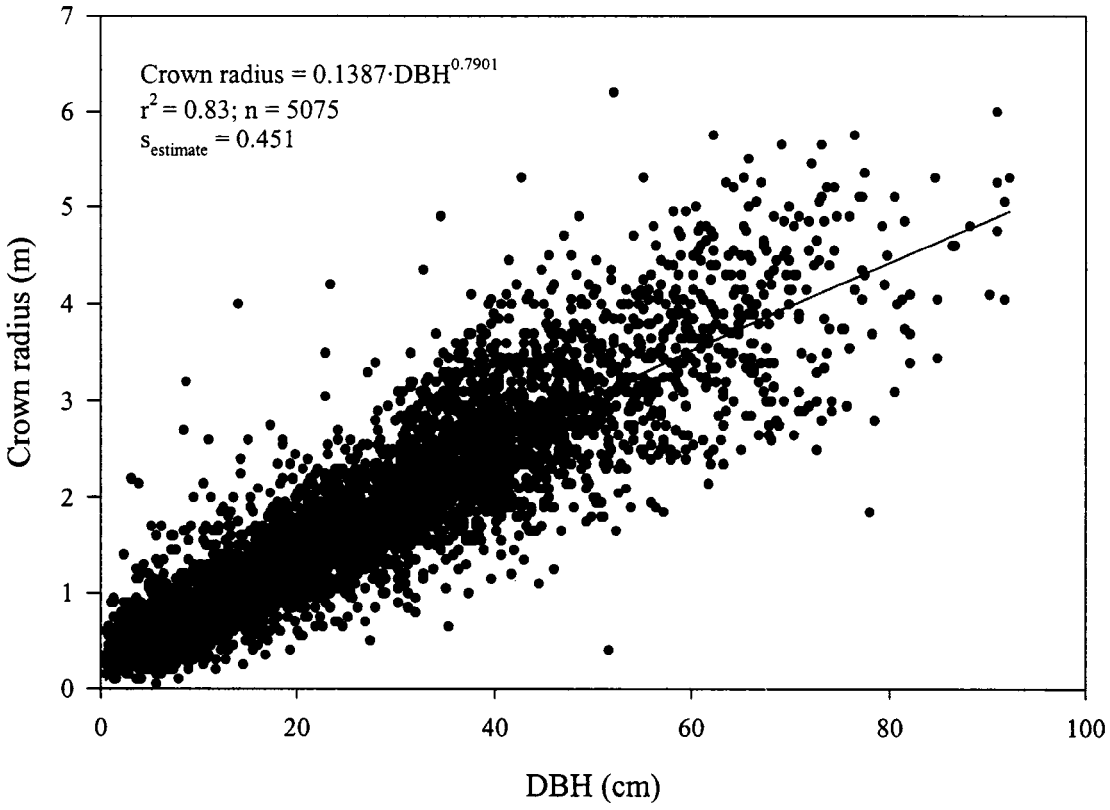

Figure 4.3. Relationship between ponderosa pine crown radius and DBH (points) with corresponding fit statistics.

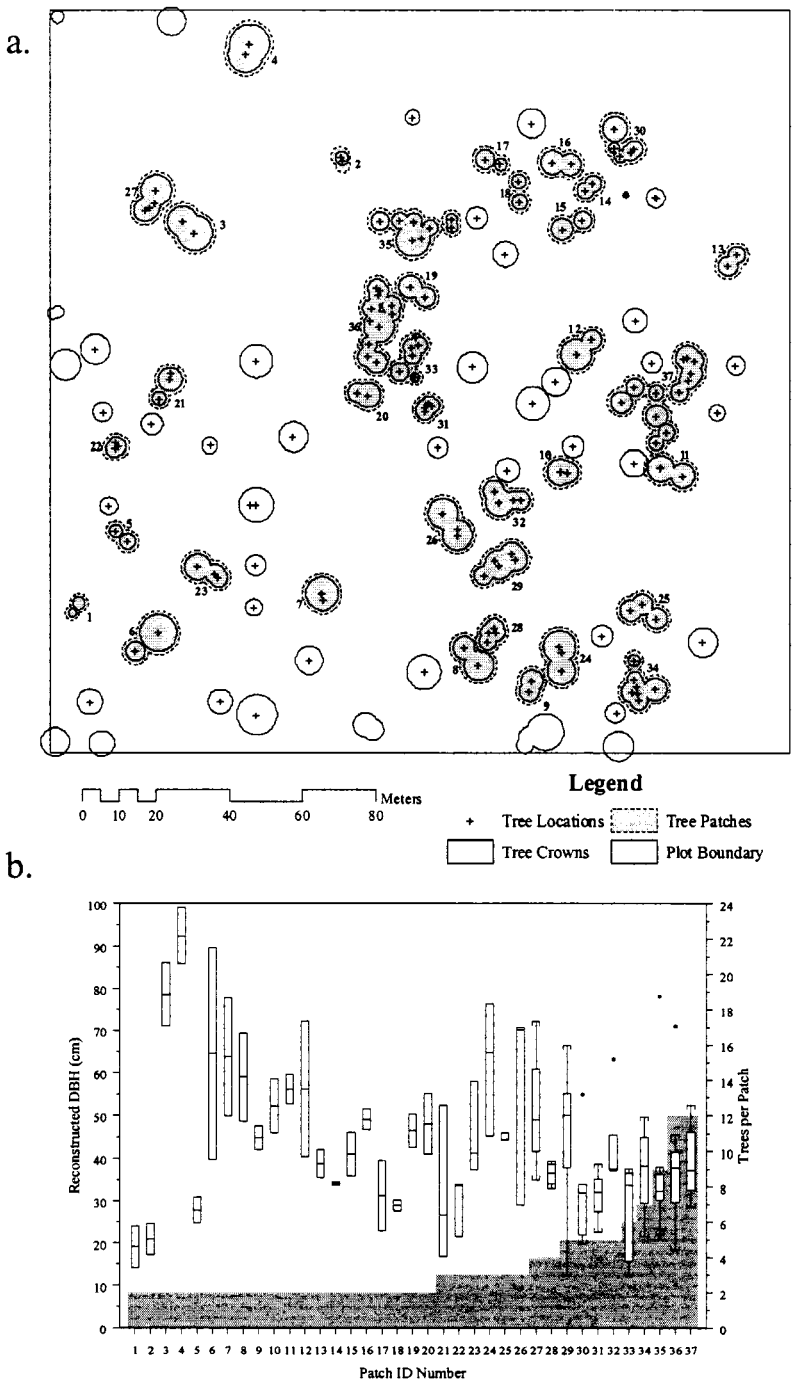

Figure 4.4. (a) Reconstructed stem-maps for COCS1B prior to Euro-American settlement (1874) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.

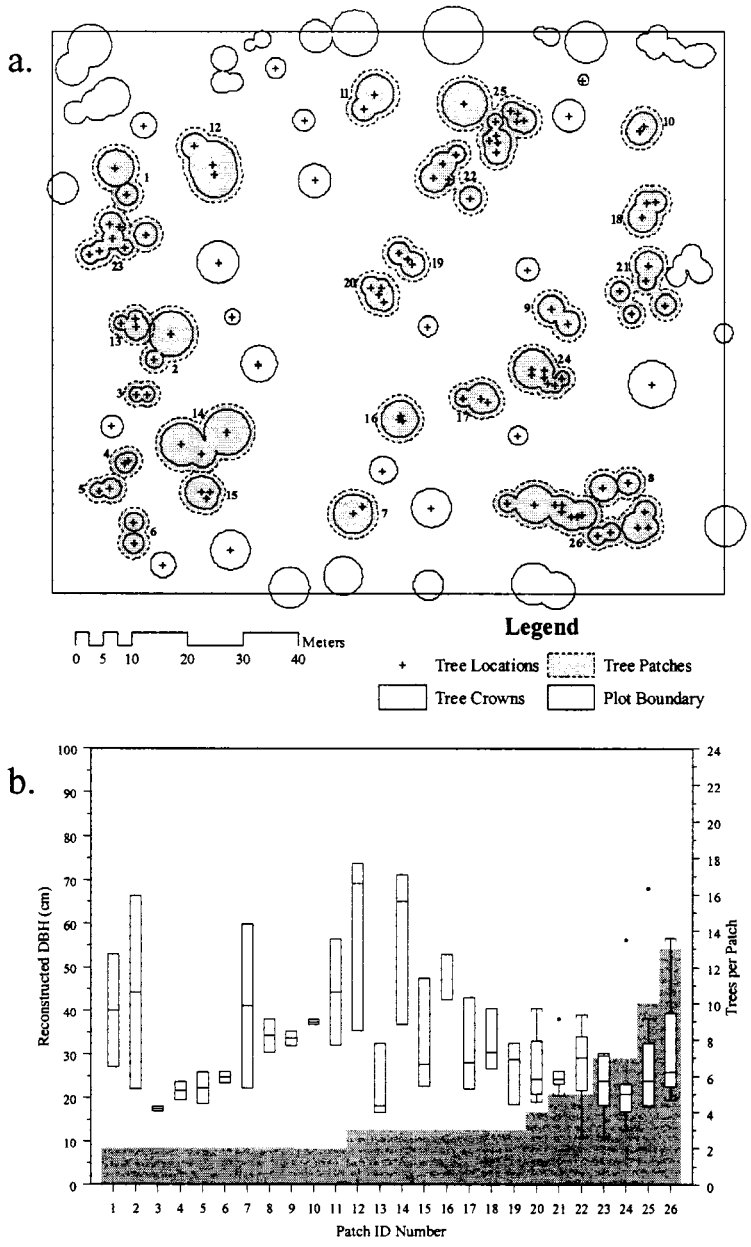

Figure 4.5. (a) Reconstructed stem-maps for COCS5B3 prior to Euro-American settlement (1873) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.

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Chapter 5

Land-Use Legacies in a Southwestern Ponderosa Pine-Gambel Oak Forest: A Case Study

Abstract

Spatial analysis of structural characteristics and recruitment patterns facilitates the understanding of past stand dynamics. I describe historical and contemporary forest patterns of a ponderosa pine-Gambel oak site that was harvested using three different harvesting systems in 1913 (Seed Tree, Group Selection, and Light Selection) and was partially excluded from livestock grazing in 1919. Using nine historically stem-mapped permanent plots for the following three stand structural scenarios: 1913 harvested (actual) and unharvested (modeled) and 2003-2006 (actual) conditions, I was able to examine the short- and long-term consequences of harvest and livestock grazing land-use and stand dynamics. I used Ripley's K(t) univariate analysis to assess changes in spatial pattern under each harvesting system and in each structural scenario. I then used Ripley's $K_{12}(t)$ bivariate analysis to examine spatial and temporal tree recruitment patterns as observed in the contemporary (2003-2006) conditions for trees ≥ 9.14 cm diameter at breast height (1.37 m). The Seed Tree harvests effectively converted the spatial patterns from aggregated to random and left few trees, while the Group Selection and Light Selection had varying effects, but consistently exaggerated the spatial patchiness of the stand. By 2003-2006, all plots were aggregated at all scales and were one large patch of

predominately small trees. Contemporary recruitment patterns were not spatially random; pine seedlings initially established in stump patches created by harvesting and then proceeded to fill-in the remaining area, with recruitment rarely found under the residual trees. Ignoring land-use legacies may lead to the misinterpretation of stand dynamics and development, and therefore should be explicitly quantified and incorporated into management and restoration activities.

Introduction

The initial settlement of the Southwest by Euro-Americans (circa 1880s) markedly changed forest structure through intensive logging, livestock grazing and fire suppression, as well as indirectly through fire exclusion (Fulé et al. 1997, Allen et al. 2002, Moore et al. 2004, Cocke et al. 2005). These legacies of past land-use practices, or land-use legacies (a.k.a. site history or disturbance history), may influence forest structure and function for decades to centuries (Foster et al. 2003). Scientists and managers recognize the importance of land-use legacies, but only when we quantify the impact of these past activities can we use that information to model contemporary or future conditions.

Land-use legacies commonly persist within heterogeneous ecosystems, including ponderosa pine (*Pinus ponderosa* Laws. var. *scopulorum*) forests, and have been shown to influence contemporary conditions (e.g., Christensen 1989, Fulé et al. 1997, Foster et al. 2003, Youngblood et al. 2004, Moore et al. 2004). An understanding of disturbance history and vegetation change provides a context for ecological studies (Christensen 1989, Pickett et al. 1997), a basis for natural resource management and planning (Moore

et al. 1999, Swetnam et al. 1999, Egan and Howell 2001), and is essential in restoration modeling (e.g., Covington et al. 2001). Contemporary management practices in southwestern ponderosa pine ecosystems must consider the historical context under which current forest structure developed and the subsequent influences of early silviculture and land management practices. Unfortunately, because of the scarcity of relict or minimally disturbed southwestern ponderosa pine forests, few studies have been able to document long-term effects of land-use legacies on stand dynamics and only a few have examined their influence on spatial pattern (Cooper 1960, 1961, White 1985, Biondi et al. 1994).

I investigated how historical land management practices, or land-use legacies, have influenced the forest structure over a 93-year period on a long-term silviculture research site in north-central Arizona. The study site is representative of ponderosa pine-Gambel oak (*Quercus gambelii* Nutt.) forest found throughout north-central Arizona, but is unusual in that different harvesting systems were applied when the study began in 1913. This dataset provides an unique opportunity to examine the interaction of historical (1913) land-use legacies and long-term (1913-2006) dynamics on forest structure and spatial pattern. My study had five questions: (1) How might forest structure have looked in the absence of Seed Tree, Group Selection and Light Selection harvesting in 1913 on a ponderosa pine-Gambel oak site in north-central Arizona? (2) How did each harvesting system affect stand characteristics and spatial patterns over the short-term (as observed in 1913 following harvest)? (3) How did stand characteristics and spatial patterns change over the long-term (as observed in 2003-2006)? (4) How did the stand structural patterns resulting from harvesting and livestock grazing influence the

recruitment of subsequent ponderosa pine cohorts across the site and within each of the three harvesting system? (5) Where did recruitment occur with respect to unharvested pine and oak trees (pine and oak), pine stumps, and natural grassy openings?

Methods

Study Site

This study was conducted on a 162-ha site, located 21 km south of Flagstaff, Arizona on the Coconino National Forest (Fig. 5.1); latitude 35°0.91′ N, longitude 111°36.26′ W. Mean annual temperature is 7.9° C and average annual precipitation at the Flagstaff weather station is 502.9 mm, following a monsoonal precipitation pattern with half of the precipitation as rain in July and August, and half as snow in the winter (Sellers and Hill 1974). Elevations range from 2240 to 2300 m and the study area has a gently rolling topography. The lowest elevations bisect the center of the site, providing both northerly and southerly aspects. Soils, derived from Tertiary basalt flows and cinders, are classified as a complex of fine, smectitic Typic Argiborolls, Lithic Eutroboralfs, and Mollic Eutroboralfs, primarily with clay loam and stony clay textures. The site is in Terrestrial Ecosystem Units 582, 585, and 586, which collectively represent over 109,000 ha (14%) of the Coconino National Forest (Miller et al. 1995). Ponderosa pine and Gambel oak are the dominant trees, with scattered New Mexican locust (*Robinia neomexicana* Gray) thickets and single alligator juniper (*Juniperus deppeana* Steud.) stems occurring throughout the study area.

Project History of Mc-2-D-3

This research site was established in 1913 as part of the Fort Valley Experiment Station (FVES). The site had not been harvested prior to the experiment initiated in 1913. The main purposes were to examine various harvesting systems and to determine the amount of protection needed to adequately shelter young trees from the sun and drying out, as well as quantify effects of harvesting and slash disposal methods on advanced regeneration, new seedling establishment, and residual tree growth (Krauch 1926, 1933, 1934, 1937, Lexen 1939, Pearson 1923, 1944, 1950). Project Mc-2-D-3 (Krauch 1916) was established by Hermann Krauch (FVES Forest Examiner) and C.F. Korstian (Silviculturist), who initially divided the site into four harvesting systems, of which the size and location of the Group Selection (56 ha), Scattered Seed Tree (61 ha), and Light Selection (45 ha and originally called "Shelterwood") systems are shown in Figure 5.1. The Scattered Seed Tree system was the only even-aged harvesting system examined. The objectives of the Scattered Seed Tree system were to leave 8 to 10 trees ha^{-1} (3 to 4 trees $acre^{-1}$) uniformly distributed across the site as a seed source and the removal of 80 percent of the sawtimber volume. The two uneven-aged harvesting systems, Group Selection and Light Selection, were established in accordance with the current harvesting practices in the region and targeted the removal of 70 and 50 percent of the volume, respectively (Krauch 1916). The site was harvested by the Flagstaff Lumber Manufacturing Company in the summer and fall of 1913.

Seven permanent plots were established within each harvest system for a total of 21 plots. I examined nine of these plots (Table 5.1), which range in size from 0.8 to 1.9 ha. Criteria used for selecting plots were: (1) plots with the largest extent were selected

as to include three plots within each harvesting system and (2) at least one of the plots selected had to be excluded from grazing. Historically and in this study, these plots are identified using the original FVES naming system, comprised of a combination of letters and numbers representing the silvicultural unit (S5), the harvesting system (Group Selection: = 1, Scattered Seed Tree = 2, or Light Selection = 3) and individual permanent plot designations (A, B, ... G). For example, S5B3 denotes permanent plot B in the Light Selection system (3) of the Fort Valley Experimental Station silviculture unit 5 (the Coulter Ranch Unit).

In addition to examining the effects of different harvesting systems, the original 1913 study also excluded livestock grazing on portions of the plots (Fig. 5.1; Table 5.1). Unfortunately, budget constraints prevented livestock exclusion from occurring simultaneously with plot establishment. Following severe damage from sheep grazing between 1913-1918 (Allison 1919), a portion of each harvesting system was fenced in 1919.

Field Measurements

All live trees with diameter at breast height (DBH; 1.37 m above ground level) ≥ 9.14 cm (3.6 in) were measured and stem-mapped at plot establishment. These stem-maps (e.g., Chapter 2, Fig. 2.1) also included the location and stump diameter of trees harvested in 1913, the location of snags and logs, and the location of seedlings. Tree condition, DBH, and other variables were recorded in a ledger that is currently housed in the USFS Rocky Mountain Research Station Fort Valley Archives, Flagstaff, Arizona. Historical (1913) and contemporary (2003-2006) field methods for measuring these plots

are detailed by Moore et al. (2004), who also report on stand structural changes within a 1.01-ha subplot of S5A2, S5B3, and 13 additional permanent plots throughout Arizona and New Mexico.

Describing stand structure

To quantify how tree spatial pattern and stand structure changed in the short-term (immediately following harvesting in 1913) and over the long-term (90+ years later), I examined the forest stand structure and spatial patterns of three stand structural scenarios on each plot: (1) '1913 unharvested' (stand structure as it would have been if harvesting had not occurred in 1913); (2) '1913 harvested' (actual 1913 stand structure); and (3) 'contemporary' (actual 2003-2006 stand structure). I restricted my attention to trees $\geq$ 9.14 cm DBH because detailed historical data were not collected for smaller trees. All tree spatial coordinates were obtained during contemporary measurements using a surveying laser. The historical stem map was used to verify that trees and stumps present at plot establishment were located correctly.

To compare stand structure and spatial patterns among scenarios, I used the location (x-y coordinates), historical stem-map, and size of all trees and stumps present in each scenario. DBH data for the contemporary scenario were obtained during contemporary measurements, and data for the harvested scenario were obtained from the 1913 plot ledgers. For the unharvested scenario, I needed to account for all trees harvested in 1913 and I needed to determine the location and size of all oak trees. Since the area was virgin prior to the 1913 harvests, sizes of the pine stems harvested were estimated by measuring the current diameter at stump height (DSH: 30 cm [12 in]) and

applying DBH-DSH regression models (Hann 1976) to predict the corresponding DBH. For the oak trees, I reconstructed the oak structure in 1913 following dendroecological methods described in detail by Fulé et al. (1997). I had to assume death dates of 1980 (Huffman et al. 2001) for all oak trees because these trees were cut for firewood and determining an exact death date was not possible.

Describing tree spatial patterns

Since spatial patterns are scale-dependent, I wanted to describe the spatial patterns of trees at multiple scales on each permanent plot for all three scenarios. I used Ripley's K(t) univariate analysis to explore the spatial arrangement of trees and their degree of "patchiness" and Ripley's $K_{12}(t)$ bivariate analysis to examine contemporary pine seedling recruitment patterns.

To determine whether the spatial pattern of individual trees changed with scale observed, I used the second-order univariate statistic, Ripley's K(t) (Ripley 1976, 1977, 1981). The Ripley's K(t) analysis examines the spatial pattern of pairs of points within various radial lag distances (t) to determine whether their distribution is random (also called complete spatial randomness or CSR), aggregated, or uniform (Upton and Fingleton 1985, Legendre 1993) and provides insight into how these patterns change with increasing scale (Upton and Fingleton 1985, Dale 1999). I used 2-m lag distances and a maximum lag distance of half the minimum dimension of each plot to reduce the error induced by edge effects (Boots and Getis 1988). Visual interpretation was simplified using a square root, variance-stabilizing transformation of K(t) to L(t)-t (Besag 1977),

and the observed L(t)-t values were tested for significance at $\alpha = 0.05$ using 99 Monte Carlo permutations (Upton and Fingleton 1985).

Describing tree recruitment patterns

In addition to the spatial pattern of individual trees, I wanted to know if the residual stand structural patterns resulting from the different harvesting systems influenced the recruitment of subsequent ponderosa pine cohorts. Specifically, I wanted to know if the cohorts established: 1) under unharvested pine trees, 2) under unharvested oak trees and/or, 3) in openings created by harvesting. To examine these associations, I treated the residual trees after the 1913 harvests as one antecedent population, the pine stumps resulting from these harvests as a second antecedent population, and the reconstructed oak (in 1913) as the third antecedent population. The spatial relationships between these three antecedent populations and the adult trees that established prior to initial harvest were then examined using Ripley's $K_{12}(t)$ bivariate analysis (Lotwick and Silverman 1982, Rowlingson and Diggle 1993, Diggle 2003). Ripley $K_{12}(t)$ bivariate analysis is conducted and interpreted in the same manner as the Ripley's K(t) analysis, except that distances are calculated between points of different populations and the confidence envelopes are formed by holding the locations of the antecedent population constant while simulating 99 toroidal shifts of the location of contemporary recruitment. This step tests a variation of the independent point processes hypothesis (Goreaud and Pélissier 2003) focusing on the spatial patterns of the contemporary pine recruitment given the spatial pattern of the three antecedent populations (McDonald et al. 2002, 2003). Ripley's K(t) univariate and Ripley's $K_{12}(t)$ bivariate analyses were conducted

using *R v.2.2.0* (R development Core Team 2005) and the *splancs* package (Rowlingson and Diggle 1993, Bivand and Gebhardt 2000).

Results

Stand structure

Live tree densities ($\geq$ 9.14 cm DBH) in 1913 for the unharvested scenario averaged 127.3 trees ha^{-1} (s = 26.9) and ranged from 75 to 164 trees ha^{-1} (Table 5.2). On the plots that were grazed (n = 5), the unharvested live tree density averaged 134.8 trees ha^{-1} (s = 22.8) and ranged from 113 to 164, while those that were eventually excluded from livestock grazing (in 1919) averaged 118.0 trees ha^{-1} (s = 32.0) and ranged from 75 to 146. Mean basal area and DBH for all plots were 19.0 m^2 ha^{-1} (s = 4.5) and 38.3 cm (s = 7.5), respectively.

The live pine tree ($\geq$ 9.14 cm DBH) densities were reduced by an average of 65% in the Seed Tree system, 44% in the Light Selection system, and 34% in the Group Selection system following their respective 1913 harvests. Residual (harvested) stand-level pine basal area averaged 6.0 m^2 ha^{-1} (s = 2.4) across all plots and ranged from 2.8 on S5B2 to 10.3 on S5B3 (Table 5.2). These values correspond to a basal area reduction of 77% in the Seed Tree system, 61% in the Group Selection system, and 57% in the Light Selection system.

Total (pine and oak combined) diameter distributions (DBH $\geq$ 9.14 cm) prior to for the 1913 unharvested scenario varied, but generally were regularly distributed across all diameter classes (Fig. 5.2). All plots had diameter distributions similar to those of multi-cohort stands (Oliver and Larson 1996), with oak comprising the majority of the

smallest diameter classes (10-30 cm). Several plots (esp. S5B2) were missing or had low pine establishment in the smallest diameter classes in 1913. S5A2 was missing the cohort of trees from the 40 cm class while S5E2 and S5B3 had the lowest proportion of oak in the 1913 unharvested scenario. All three harvesting systems consistently harvested the largest diameter trees (> 60 cm, see Fig. 5.3) and the Group Selection had the least effect on the diameter distributions.

Contemporary (2003-2006) live tree ($\geq$ 9.14 cm DBH) densities of both pine and oak combined averaged 693.3 (s = 347.6) trees ha^{-1} and ranged from 316 to 1492 (Table 5.2). As compared to the unharvested scenario, tree densities increased by an average of 3.7 times in the Light Selection system, 4 times in the Group Selection system, and 9.2 times in the Seed Tree system. On the plots that were grazed by livestock (n = 5), the contemporary tree densities (for both pine and oak combined) averaged 516.2 trees ha^{-1} (s = 143.4), while those that were excluded from livestock grazing in 1919 (n = 4) averaged 914.7 trees ha^{-1} (s = 420.9).

Contemporary mean basal area and DBH for all plots (regardless of grazing history) had increased to 34.2 m^2 ha^{-1} (s = 12.4) and decreased to 21.0 cm (s = 5.1), respectively. Contemporary diameter distributions (DBH $\geq$ 9.14 cm) tended to exhibit an inverse J-shaped distribution (Fig. 5.2).

Tree spatial patterns

Live pine trees were significantly aggregated under all scenarios (Table 5.3) with trees being more strongly aggregated in the 1913 harvested scenario (excluding S5B2, which exhibited CSR). In the unharvested and harvested scenarios, the live pine tree

locations exhibited distinct peaks in aggregation from 4 to 16 m lag distances (e.g., Fig. 5.3e,f), indicating that historical patches of trees were approximately 0.005 ha to 0.08 ha in size. However, the heights of these peaks were much larger for the harvested than unharvested scenario, indicating that the harvest exaggerated the patchiness of the stand. In the unharvested scenario, trees were consistently aggregated at distances up to 12 m and randomly distributed at scales greater than 32 m. In the harvested scenario, general trends in spatial pattern (aggregation) were similar to those observed in the 1913 unharvested scenario (Table 5.3). Also, the maximum scale at which trees were found to be aggregated in the harvested scenario for the Seed Tree and Group Selection systems increased, but changed little in the Light Selection system (Table 5.3; also see Fig. 5.3e,f).

In the contemporary scenario, distinct small patches were no longer discernable in plots harvested using the Seed Tree system, yet trees were still found to be aggregated (except S5A2) at all spatial scales up to the maximum distance tested (Table 5.3). While trees were also aggregated at all spatial scales up to the maximum distance tested in the Group Selection and Light Selection system, broad peaks were discernable (e.g., Fig. 5.3d - around 22 m) and likely resulting from increases in patch size through recruitment on previously unoccupied sites (Fig. 5.4).

Tree recruitment patterns

Several distinct patterns that emerged from the Ripley's $K_{12}(t)$ bivariate analysis (Table 5.4) were: (1) random association (CSR) with the locations of the reconstructed live oak trees at all scales sampled with isolated observations of positive (S5G1) or

negative (S5D3 and S5F3) association at two to four lag distances; (2) positive association or aggregation with the stump locations on all sites at varying lag distances (e.g., Table 5.4); and (3) negative association or repulsion with the unharvested live pine tree locations at scales under 28 m across all sites, with S5B2 being the only exception .

As expected, the spatial association among pine recruitment in the Seed Tree system was either randomly associated with unharvested pine, which were few in number (< 31 trees ha^{-1}; Table 5.2), or found to be negatively associated at small distances. S5B2 (Fig. 5.5), which was the most intensely harvested plot sampled (residual density of 10.7 tree ha^{-1}), shows how initial seedlings established near pine stumps, while later cohorts colonized the plot indiscriminately (Fig. 5.6).

More consistent patterns were found on the plots that received Group Selection and Light Selection harvests (Fig. 5.7 and 5.8). For these systems (n = 6) plots exhibited negative association with the live tree locations and positive association with the stump locations. Random associations with oak were found at all scales sampled across all plots except S5G1 and S5B3, which exhibited small scale ($\leq$ 8 m) positive association and too few oak to make any inferences, respectively. The attraction of initial cohorts to the newly created openings (stump patches) was well documented by repeat photography (Fig 5.9 and 5.10). Initial and subsequent cohorts appeared to be rarely recruited under unharvested live pine trees. For example, the pattern can be seen in the lack of recruitment observed under unharvested live trees on the south half of plot S5B1 (Fig. 5.7) and the great numbers recruited on S5B3 in areas that historically (1913 unharvested scenarios of the Light Selection harvest) had no trees (Fig. 5.8).

Discussion

Harvesting systems used and livestock exclusion in the early 1900s increased tree densities and exaggerated the patchiness of the ponderosa pine-Gambel oak stands examined in this study. Overall, both pine and oak densities increased with each harvest system, but the seed tree had the largest increase and the light selection had the least. Tree density increases were even greater on plots where livestock grazing was excluded, regardless of harvest method. All harvesting systems changed the spatial pattern of the unharvested forest. Seed tree harvests changed the pattern from patchy (aggregated) to random, while the group and light selection methods exaggerated the patchiness of the pine-oak forest to some degree. Lastly, over the past 90 years, post-harvest pine recruitment occurred mostly commonly in interspaces or canopy gap (either a grass opening or on a stump patch) and away from older, live trees or residual tree patches.

Stand structure

Prior to Euro-American fire exclusion (circa 1881-1883 [Fulé et al. 1997, Van Horne and Fulé 2006]), seedling establishment was infrequent due to the low-intensity fire regime and subsequent competition from herbaceous plants (Cooper 1960, White 1985, Bailey and Covington 2002). Contemporary stand conditions (increased density and smaller trees) most likely resulted from numerous pulses of pine establishment in the early 1900s (Savage et al. 1996) following heavy livestock grazing and intensive harvesting systems (e.g., seed tree system). Intense grazing provided favorable seedbeds for seedling establishment, similar to those created historically by fire or more recently by harvesting, and when combined with fire exclusion would allow an unusually high

density of trees to become established and persist (Cooper 1960, White 1985, Mast et al. 1999, Moore et al. 2004, Bakker 2005). This density would have included a cohort that became established after the last fire event prior to Euro-American fire exclusion. Similarly to a previous study (Chapter 2), I suggest that following fire exclusion and initial disturbance, new cohorts initiated in waves of establishment until growing space was fully utilized, then recruitment essentially stopped.

Comparing the stand structure of the unharvested scenario to presettlement conditions reported for nearby areas, pine and oak densities on my study area were greater than the 43 pine trees ha^{-1} and 4 oak trees ha^{-1} found by Covington and Moore (1994) at Bar-M Canyon, the 43 pine trees ha^{-1} found by Fulé et al. (1997), and the range of 62 to 72 pine trees ha^{-1} found by Fulé at al. (2002) for sites on the south rim of Grand Canyon National Park. These historically high densities suggest the effects of fire exclusion and livestock grazing were evident as early as 1913 (Krauch 1916, Woolsey 1920). Fulé et al.'s (1997) estimate of presettlement oak density was 20 times higher than that reported by Covington and Moore (1994), twice as high as the average found in this study, and only slightly higher than those reported by Fulé et al. (2002). Tree densities on my study area also fall within the range of 40 to 255 trees ha^{-1} reported in several early National Forest inventories and other studies in the region (see Chapter 3, Table 3.1 for comparison). Fulé et al's (1997) 1883 Camp Navajo reconstructions report relatively high densities of small-diameter oaks, which was similar to the conditions found on several plots examined in this study (S5A2, S5C1, S5F3). Fulé et al. (1997) hypothesized that since Gambel oak reproduces vegetatively and is highly susceptible to fire, it is likely that many or most of these small trees would have been thinned had fires

continued after fire exclusion and that the density of larger oaks may be more representative of the long-term average oak density under a continuing frequent fire regime. Their estimate of presettlement oak density over 10 cm DBH was 33 oaks ha^{-1} and very near to those reported in this study.

The observed increase in ponderosa pine and Gambel oak tree density by 2003-2006 is consistent with the structural changes in ponderosa pine ecosystems reported throughout Arizona (Cooper 1960, White 1985, Covington and Moore 1994, Fulé et al. 1997, Mast et al. 1999, Fulé et al. 2002 Moore et al. 2004) and in related long-needled pine ecosystems throughout western North America (Covington et al. 1994). The contemporary density of ponderosa pine is very close to the 1997-1999 average of 520 trees ha^{-1} reported by Moore et al. (2004) but less than the 690 to 956 trees ha^{-1} range reported by Fulé et al. (2002) for the south rim of Grand Canyon National Park, the 1900 tree ha^{-1} reported by Covington and Moore (1994) at Bar-M Canyon, and the 720 trees ha^{-1} reported by Fulé et al. (1997) for the Camp Navajo Army National Guard facility. Contemporary oak densities very similar to the 156 trees ha^{-1} reported at Bar-M Canyon (Covington and Moore 1994a) and the average 138-182 oaks ha^{-1} reported by Barger and Ffolliott (1972) in a central Arizona ponderosa forest.

Tree spatial patterns

Historically, unharvested stands on this study site were composed of tree patches averaging 0.005 to 0.08 ha in size with interspaces heavily grazed by livestock. The contemporary stand structure, all sites and regardless of harvesting system used, may be best characterized as a single large patch ($\geq$ 1.9 ha).

Under the unharvested scenario, the pine patch sizes I found were on the lower end of the ranges reported by Cooper (1961), White (1985), and in the previous chapter (Chapter 4). Cooper (1961) found that trees in east-central Arizona were aggregated into distinct patches ranging from 0.06 to 0.14 ha. White (1985), who conducted his study in the nearby Gus Pearson Natural Area, determined that ponderosa pine trees were strongly aggregated and occupied areas ranging from 0.02 to 0.29 ha in size. In the previous chapter, I found reconstructed presettlement patch sizes to range from 0.01 to 0.15 ha in size on six pure ponderosa pine plots. While the patch sizes reported for this study were smaller, they did overlap considerably and represent patches in a mixed species (pine and oak) system. As discussed in Chapter 2, the reason for the differences in patch size between Cooper (1961), White (1985), and this study is most likely the method by which patches were quantified, which was different in all three studies.

My results showed that the initial harvests in 1913 had varying effects. Harvests in the Seed Tree system generally resulted in random spatial patterns, while the Group Selection and Light Selection systems did not affect or only slightly increased tree patch size. This is especially true for the plots in the Light Selection system (e.g., S5D3), suggesting that my tree patch sizes were similar to White's (1985) results, as his study area also received a light selection harvest in 1894. Over the last 90+ years, however, tree patch size has generally increased and the plots in my study area have become homogenized with respect to spatial pattern. The observed increase in tree density over time is likely due to an increase in the number of tree patches (recruitment of new patches) rather than tree recruitment into pre-harvest patches (see Chapter 2).

Tree recruitment patterns

Contemporary trees, in general, are aggregated up to the largest measured scale ($\leq$ 60 m) and historically unharvested plots were found to be most strongly aggregated ($\leq$ 28 m) only at smaller spatial scales. This difference is likely a product of different processes acting upon the spatial distributions of both small and large trees (e.g. processes acting at upon seedling establishment and recruitment patterns vs. the harvested patterns of older cohorts). The more aggregated distribution of the largest contemporary trees (those that were not harvested) is likely an artifact imposed by land-use legacies, especially past harvesting practices.

My results suggested that pine recruitment patterns varied both between and within areas that received different harvests, but was highest in interspaces or canopy gap openings produced by either harvesting or pre-existing ones that were heavily grazed by livestock. These findings are consistent with findings from numerous other studies (Pearson 1923, Cooper 1960, White 1985, Mast and Veblen 1999, Boyden et al. 2005). The results of the Ripley's $K_{12}(t)$ bivariate analyses and trends captured by repeat photography series (e.g., Fig. 5.7 and 5.9) suggest that post-harvest recruitment patterns were not spatially random and pine seedlings initially established in the grazed interspaces, and were followed closely thereafter by cohorts establishing around the stump patches created in 1913. Several of the plots within the study site were fenced in 1919 (Table 5.1), which in turn, likely released these seedlings from trampling and/or grazing and contributed to the increased tree densities seen on these sites today (Bakker 2005).

Case Study Constraints

Clear differences were observed in tree patterns among the three harvesting systems but the ability to draw causal inferences is limited by the lack of treatment replication, a common problem in assessing change using retrospective studies (Carpenter 1990) and case studies in general. However, the original researchers did recognize the need to install plots that captured the variability of the site (elevation, slope, slope position, initial tree densities), thus permitting inferences on the influence of tree patterns with respect to harvesting system.

Three additional sampling constraints should be noted. Firstly, the contiguous area of each plot or stem-map used in this study may not be large enough to capture the spatial process of interest (Dale 1999). While these plots might be considered small, I am confident that they are of adequate extent to capture individual tree and/or patch processes since the smallest extent examined (0.8 ha) was three times greater than the maximum patch size (0.29 ha) reported by White (1985) and because the minimum lag distance examined on all sites (40 m) was equal to or larger than those reported for similar studies (e.g., Mast and Veblen 1999, Boyden et al. 2005). Another sampling issue is the small sample size of plots, clustered together in one area, which only represent 17% of the Coconino National Forest. And, lastly, since the plots I used in this study had different harvest and grazing treatments, do they represent either the historical and/or the contemporary forest? The latter two issues raise concerns about the applicability of my case study results to the larger, heterogeneous landscape of ponderosa pine forests in north-central Arizona (Bell 2005). However, there have been a few studies (Moore et al. 2000, Bell 2005, Moore et al. 2004) showing that these historical permanent plots were

reasonably representative in structure and composition of the broader region in the historical context, lending some degree of support to extrapolating inferences about historical small-scale spatial patterns on these plots. Finally, is should be noted that these data do not represent presettlement reference conditions (Kaufmann et al. 1994, Morgan et al. 1994, Fulé et al. 1997, Moore et al. 1999) since the 1913 unharvested scenarios embodies some 30+ years of fire exclusion intense livestock grazing. However, given the relatively little regeneration observed at plot establishment (Krauch 1916) and the range of DBH growth reported for the first 5 years following plot establishment (0.6-3.8 cm; Krauch [1926]), I expect attributes such as spatial pattern and stand density for trees ≥ 9.14 cm DBH to have changed little.

Management Implications

The long-term changes in forest structure and spatial patterns reported in this study have importance relative to current and future forest management by adding explanatory power to the understanding of how contemporary conditions came about and inform management for future conditions (Foster et al. 2003). Understanding land-use legacies and their enduring consequences on forest structure and spatial patterns, decades later after they have occurred, can increase the effectiveness of management (Swetnam at al. 1999). In contrast, ignoring land-use legacies may lead to the development of ill-conceived restoration and management schemes (Foster 2000).

Spatial analysis of structural characteristics and recruitment patterns facilitates the understanding of past stand dynamics. At this ponderosa pine-Gambel oak site, valuable insight into the long-term consequences of land-use legacies and regeneration episodes

are provided. By applying various analysis techniques to spatially-explicit data, detailed information can be derived on key variables (i.e., tree density, mean patch size, spatial pattern of tree establishment) that may, in turn, be applied within restoration and management efforts. For example, spatial patterns of reconstructed ponderosa pine plots suggest that the mosaic of tree patches within a relatively open matrix advocated by Meyers and Sisk (2001) for improving invertebrate habitat and by Laughlin et al. (2006) to increase herbaceous production are indeed within the range of conditions exhibited by historical forests. Alternatively, the absence of closed canopy forest conditions prior to active management suggest that some wildlife habitat conditions, such as those mandated for northern Goshawk on Forest Service lands throughout Arizona and New Mexico (USFS 1996), are outside the range of historical forest conditions.

Examining the influence of land-use legacies places contemporary stand conditions in the context of stand dynamics, which embody past land management practices (harvesting, livestock grazing, fire exclusion), and natural disturbances. While these past management activities are know to shape current conditions, they also constrain future responses and possibilities (Foster et al. 2003). Meanwhile, contemporary land management practices, or future land-use legacies, continue to add additional layers of complexity to current structure and spatial patterns. Considering this perspective, the importance of designing and implementing long-term ecological experiments and monitoring programs is obvious.

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Table 5.1. Plot descriptions and management histories for nine historical permanent plots established in 1913 on the Coconino National Forest (Arizona).

Plot	Size (ha)	Elevation (m)	TEU[a]	Livestock Excluded	Harvesting System
S5A2	1.2	2300	585	N	Seed Tree
S5B2	1.2	2272	585	Y	"
S5E2	1.0	2239	582/585	Y	"
S5B1	1.9	2260	585/586	Y	Group Selection
S5C1	1.2	2272	585	N	"
S5G1	0.8	2267	585	N	"
S5B3	1.2	2255	582/585	Y	Light Selection
S5D3	0.8	2262	585	N	"
S5F3	0.8	2255	585	N	"

[a] Terrestrial Ecosystem Unit (Miller et al. 1995) soil order: 582 = Typic Argiborolls and Mollic Eutroboralfs; 585 = Lithic Eutroboralfs; 586 = Mollic Eutroboralfs and Lithic Eutroboralfs.
[b] Sites excluded from livestock grazing by fencing in 1919.

Table 5.2. Average stand attributes for nine historical permanent plots on the Coconino National Forest (Arizona) for three scenarios: 2003-2006 contemporary, 1913 harvested (actual 1913 structure), and unharvested (reconstructed structure in absence of harvesting)

Treatment	Plot	Species	Contemporary			1913 Harvested[b]			1913 Unharvested[a]		
			Density (Tree ha^{-1})	Basal Area (m^2 ha^{-1})	DBH±SD (cm)	Density (Tree ha^{-1})	Basal Area (m^2 ha^{-1})	DBH±SD (cm)	Density (Tree ha^{-1})	Basal Area (m^2 ha^{-1})	DBH±SD (cm)
Seed Tree	S5A2	Pine	558.4	30.8	24.4±10.4	18.9	3.1	37.7±26.5	45.3	13.0	55.3±24.8
	"	Oak	153.2	5.8	19.8±9.7	-	-	-	76.6	2.3	17.3±9.4
	"	Total	711.6	36.6	23.4±10.4	-	-	-	121.9	15.3	31.4±24.9
	S5B2*	Pine	1341.8	57.3	8.2±4.1	10.7	2.8	53.1±23.6	83.2	23.6	57.5±17.7
	"	Oak	149.9	5.6	7.1±4.9	-	-	-	62.6	3.7	24.6±16.3
	"	Total	1491.7	62.9	8.1±4.2	-	-	-	145.8	27.3	44.3±23.5
	S5E2*	Pine	902.4	41.3	21.5±11.1	30.6	5.1	39.7±23.6	59.3	15.3	51.9±24.7
	"	Oak	26.7	1.1	20.7±10.6	-	-	-	14.8	0.9	22.3±18.3
	"	Total	929.1	42.4	21.4±11.0	-	-	-	74.1	16.3	46.0±26.3
Group Selection	S5B1*	Pine	569.9	25.9	21.4±11.0	52.0	4.8	31.0±14.4	89.6	14.6	41.3±19.4
	"	Oak	157.5	3.7	16.2±6.4	-	-	-	47.4	1.4	17.5±9.0
	"	Total	727.4	29.6	20.3±10.4	-	-	-	136.9	16.1	33.1±20.0
	S5C1	Pine	350.1	25.1	27.4±12.7	66.7	5.7	30.1±13.6	89.8	15.7	41.0±23.4
	"	Oak	168.9	4.5	16.9±7.6	-	-	-	74.1	2.2	17.2±9.7
	"	Total	518.9	29.6	24.0±12.3	-	-	-	163.9	17.9	30.2±22.0
	S5G1	Pine	415.1	23.5	23.7±12.6	64.2	6.5	33.5±12.8	95.1	13.5	39.3±16.4
	"	Oak	147.0	4.3	17.7±7.8	-	-	-	59.3	2.1	17.7±11.4
	"	Total	562.2	27.8	22.1±11.8	-	-	-	154.4	15.6	31.0±18.1
Light Selection	S5B3*	Pine	506.6	27.7	21.9±14.8	83.2	10.3	36.8±14.7	113.7	18.7	41.9±18.5
	"	Oak	4.1	0.0	12.8±3.7	-	-	-	1.6	0.1	25.5±22.3
	"	Total	510.7	27.7	21.8±14.7	-	-	-	115.3	18.8	41.6±18.5
	S5D3	Pine	282.9	19.3	25.7±14.5	50.7	6.8	37.9±16.7	93.9	17.6	45.6±17.8
	"	Oak	33.4	1.3	20.0±9.0	-	-	-	18.5	0.5	17.4±4.5
	"	Total	316.3	20.6	25.1±14.2	-	-	-	112.4	18.1	41.0±19.5
	S5F3	Pine	380.5	22.0	24.3±12.1	37.1	8.8	50.9±21.3	89.0	25.0	57.1±17.9
	"	Oak	229.8	8.8	18.1±7.4	-	-	-	32.1	0.9	17.0±8.6
	"	Total	472.0	30.8	23.1±11.6	-	-	-	121.1	25.9	46.5±23.9

[a] Oak stand attributes reconstructed using contemporary data.
[b] Post-harvest stand attributes reported for pine only.
* Plot excluded from grazing in 1919.

Table 5.3. Ripley's K(t) univariate statistic, transformed as [L(t)-t]) as a function of lag distance (m) trees (≥ 9.14 cm DBH) in three scenarios: 2003-2006 contemporary, 1913 harvested (actual 1913 structure), and unharvested (stand structure as it would have been if harvesting had not occurred in 1913) on nine historical permanent plots examined for three harvesting systems: Seed Tree, Group Selection, and Light Selection. Statistical significance at the 95% level is indicated by (+) for aggregated and (–) for uniform patterns; blank values indicate random pattern; na = t not applicable at that scale.

Scenario	Treatment	Plot	Distance (m)																														
			2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60
2003-2006 Contemporary	Seed Tree	S5A2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							-	-	na	na	na	na	na
		S5B2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
		S5E2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
	Group Selection	S5B1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
		S5C1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
		S5G1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na	na	na	na	na	na
		S5B3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
	Light Selection	S6D3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na	na	na	na	na	na
		S5F3	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na	na	na	na	na	na
1913 Harvested	Seed Tree	S5A2	+	+	+	+	+	+	+	+	+	+																	na	na	na	na
		S5B2																											na	na	na	na
		S5E2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+					na	na	na	na
	Group Selection	S5B1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
		S5C1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na
		S5G1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+							na	na	na	na	na	na	na	na	na
		S5B3	+	+	+	+	+	+	+	+	+	+	+	+	+	+													na	na	na	na
	Light Selection	S6D3	+	+	+	+	+	+	+	+					-	-		-						na	na	na	na	na	na	na	na	na
		S5F3			+	+	+	+	+	+	+	+	+											na	na	na	na	na	na	na	na	na
1913 Unharvested	Seed Tree	S5A2	+	+	+	+	+	+	+																				na	na	na	na
		S5B2	+	+	+	+	+	+	+	+	+	+	+	+		+	+		+									-	na	na	na	na
		S5E2	+	+	+	+	+	+	+	+	+																		na	na	na	na
	Group Selection	S5B1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+													
		S5C1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+											na	na	na	na
		S5G1	+	+	+	+	+	+	+	+	+	+	+	+	+									na	na	na	na	na	na	na	na	na
		S5B3	+	+	+	+	+	+	+	+	+	+									-	-		-	-	-	-	-	na	na	na	na
	Light Selection	S6D3	+	+	+	+	+	+	+						-									na	na	na	na	na	na	na	na	na
		S5F3	+	+	+	+	+	+	+	+	+	+												na	na	na	na	na	na	na	na	na

Table 5.4. Ripley's $K_{12}(t)$ bivariate statistic, transformed as $[L_{12}(t)-t]$) as a function of lag distance (m) for contemporary (2003-2006) pine recruitment vs. pine stumps, pine, and oak tree ($\geq$ 9.14 cm DBH) locations on nine historical permanent plots examined for three harvesting systems: Seed Tree, Group Selection, and Light Selection. Statistical significance at the 95% level is indicated by (+) for attraction and (–) for repulsion; blank values indicate random spatial association; na = t not applicable at that scale.

			Distance (m)																													
Treatment	Class	Plot	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60
Seed Tree	Stumps	S5A2	+		+	+	+	+	+	+	+	+	+	+	+	+												na	na	na	na	na
	Pine	S5A2	-	-	-	-	-	-	-	-	-	-	-	-														na	na	na	na	na
	Oak	S5A2																										na	na	na	na	na
	Stumps	S5B2	+																									na	na	na	na	na
	Pine	S5B2	-	-	-	-	-											+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
	Oak	S5B2																										na	na	na	na	na
	Stumps	S5E2	+	+		+	+							+	+	+	+	+										na	na	na	na	na
	Pine	S5E2																										na	na	na	na	na
	Oak	S5E2																										na	na	na	na	na
Group Selection	Stumps	S5B1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Pine	S5B1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Oak	S5B1																													+	+
	Stumps	S5C1					+			+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+	na	na	na	na	na
	Pine	S5C1			-	-	-	-	-	-	-	-																na	na	na	na	na
	Oak	S5C1																										na	na	na	na	na
	Stumps	S5G1	+	+	+	+	+	+											+				na	na	na	na	na	na	na	na	na	na
	Pine	S5G1				-	-	-	-	-	-	-	-	-	-	-	-	-					na	na	na	na	na	na	na	na	na	na
	Oak	S5G1	+	+	+	+																	na	na	na	na	na	na	na	na	na	na
Light Selection	Stumps	S5B3	+	+	+	+	+	+																				na	na	na	na	na
	Pine	S5B3		-	-	-	-	-	-	-	-	-	-	-	-	-												na	na	na	na	na
	Oak	S5B3	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
	Stumps	S5D3	+					+	+														na	na	na	na	na	na	na	na	na	na
	Pine	S5D3		-	-	-	-	-	-	-	-	-											na	na	na	na	na	na	na	na	na	na
	Oak	S5D3				-	-	-	-														na	na	na	na	na	na	na	na	na	na
	Stumps	S5F3												+	+	+	+	+	+	+	+		na	na	na	na	na	na	na	na	na	na
	Pine	S5F3		-	-	-	-	-	-	-	-												na	na	na	na	na	na	na	na	na	na
	Oak	S5F3				-	-																na	na	na	na	na	na	na	na	na	na

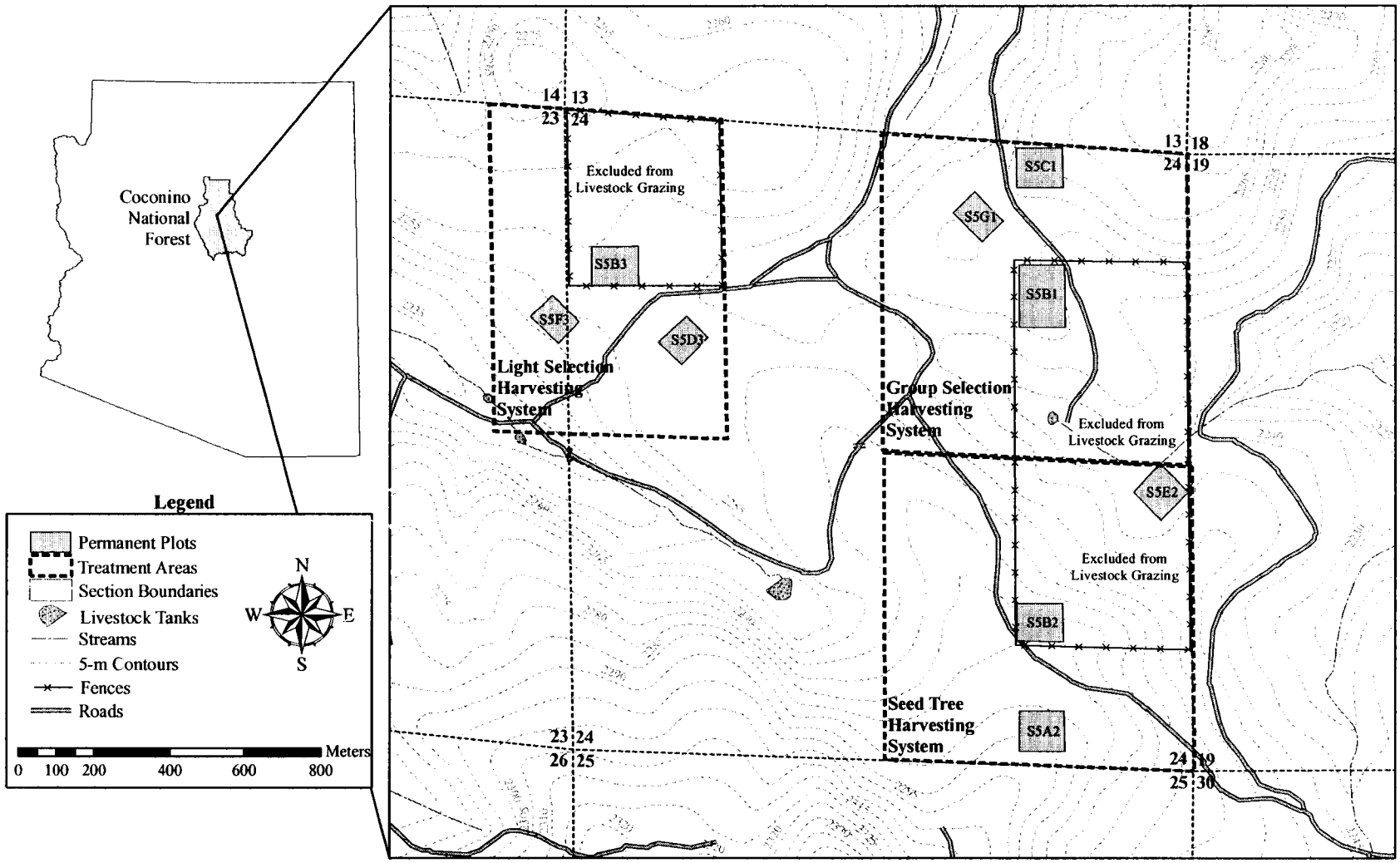

Figure 5.1. Study site (historical "Coulter Ranch Unit"), Coconino National Forest, Arizona.

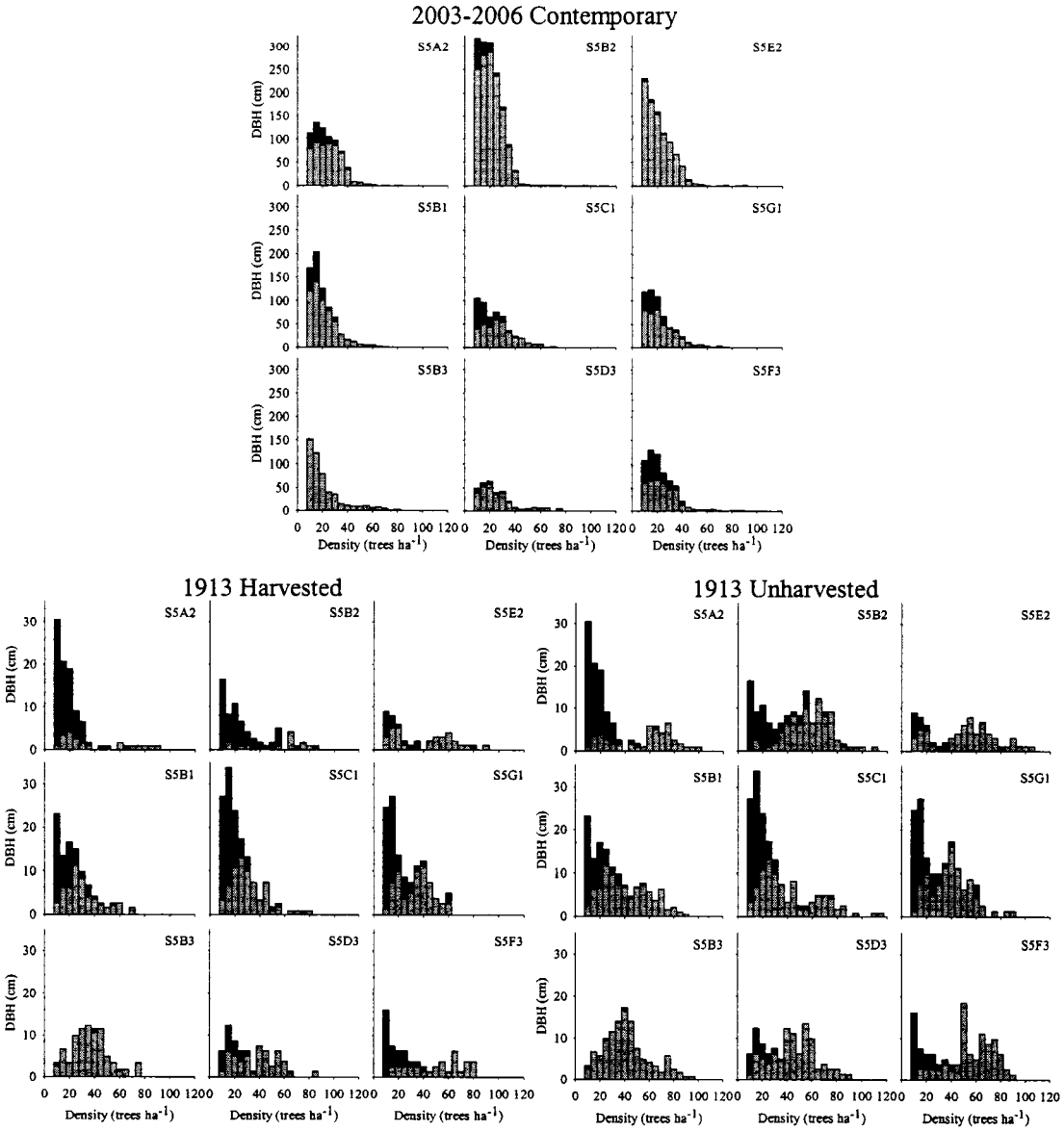

Figure 5.2. Partial (live trees ≥ 9.14 cm DBH) diameter distributions for pine (light grey) and oak (dark grey) on nine historical permanent plots examined under three structural scenarios: 2003-2006 contemporary, 1913 harvested (actual structure) and 1913 unharvested (reconstructed structure in absence of harvesting).

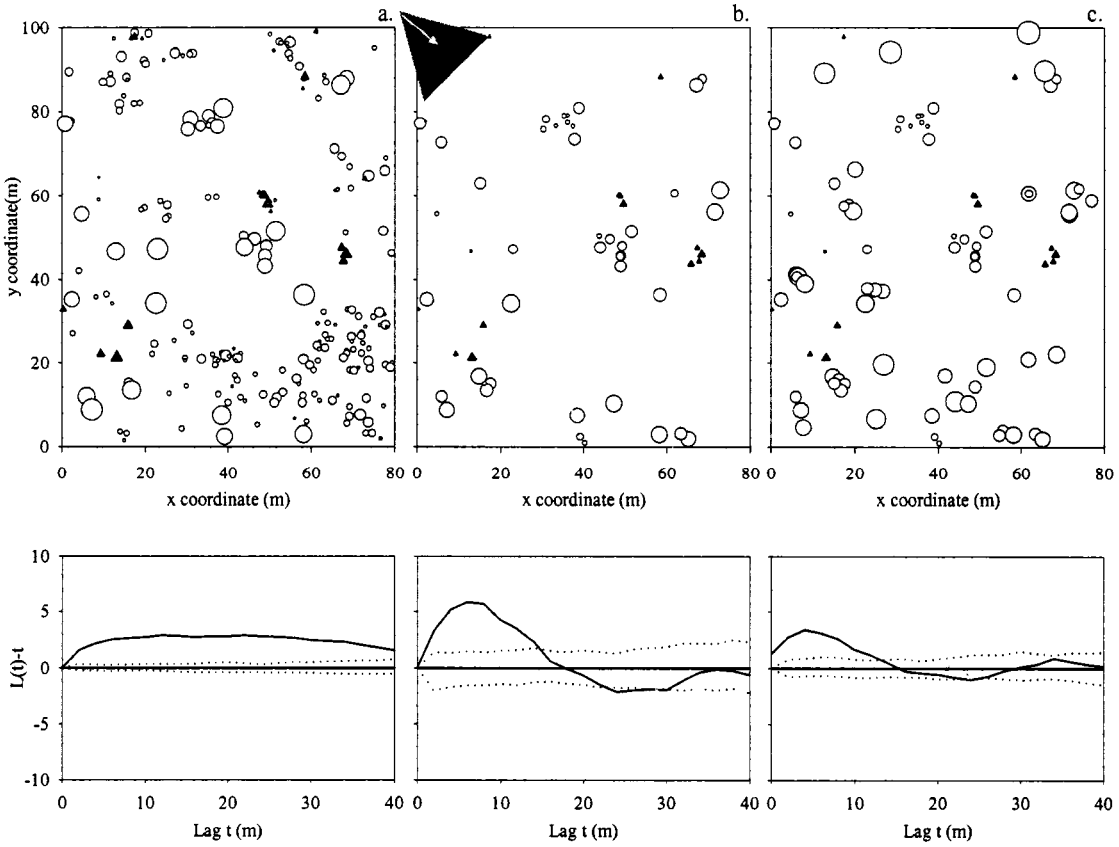

Figure 5.3. Stem maps (top) and Ripley's K(t) univariate statistic, transformed as [L(t)-t]) as a function of lag distance(bottom) for S5D3 of live trees ≥ 9.14 cm DBH in three scenarios: (a) contemporary (2003-2006, n = 256), (b) harvested (actual 1913 structure, n = 64), and (c) unharvested (stand structure as it would have been if harvesting had not occurred in 1913, n = 99). Point size is proportional to pine (open circles) and oak (closed triangles) stem diameter and on a different scale from tree coordinates for visual clarity. Arrow denotes repeat photo point location and shaded area denotes field of view.

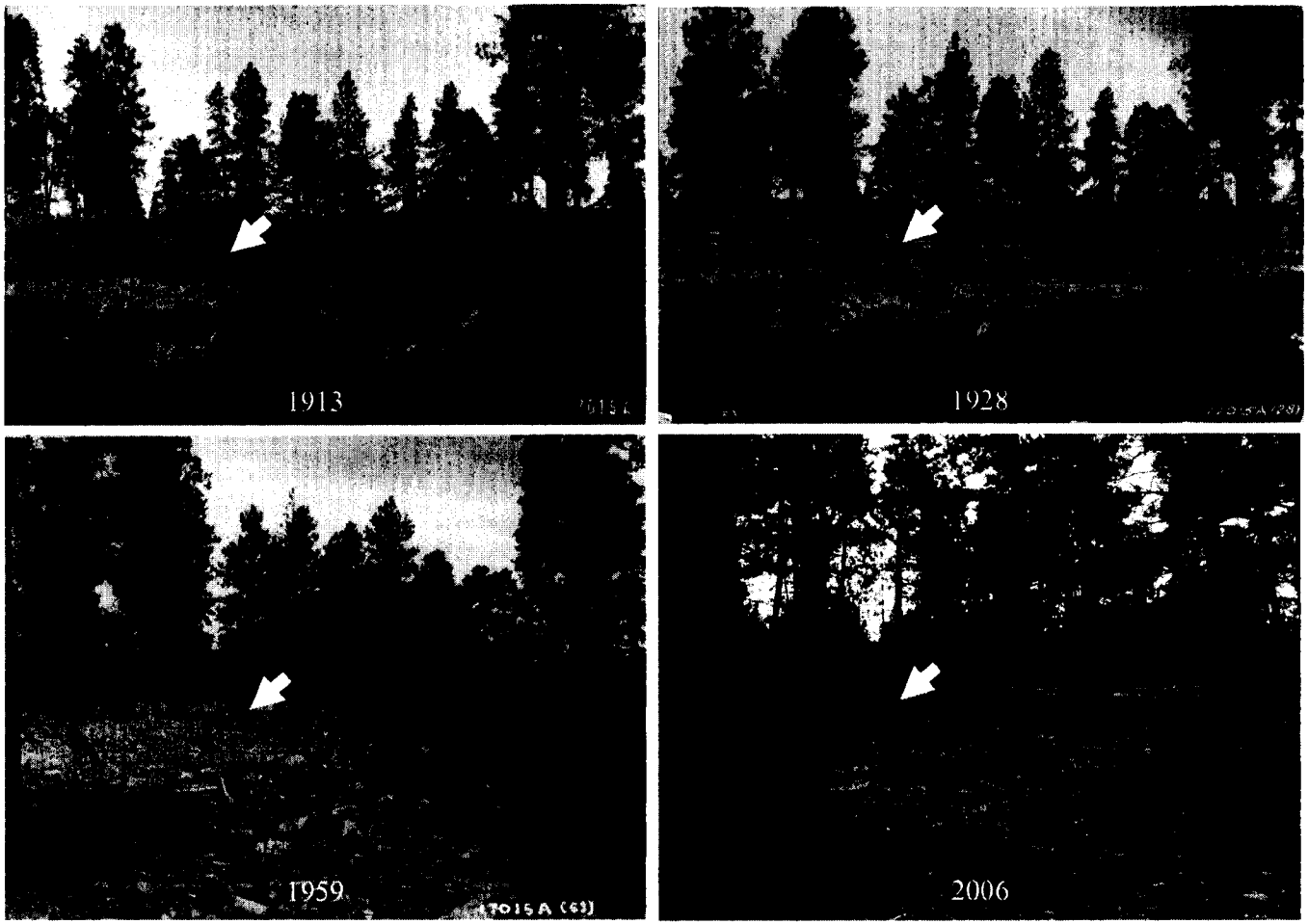

Figure 5.4. 1913 (top left), 1928 (top right), 1959 (bottom left), and 2006 (bottom right) photographs taken on S5D3 (Light Selection System). Repeat photo point location shown in Figure 5.3. The 1913 and 1928 photos were taken by H. Krauch (US Forest Service photo 17017A), the 1959 photo by M.M. Larson (US Forest Service photo LA-144), and the 2006 photo by A.J. Sánchez Meador. Note uneven-aged recruitment near stump (arrow) and persistence of grassy opening in foreground.

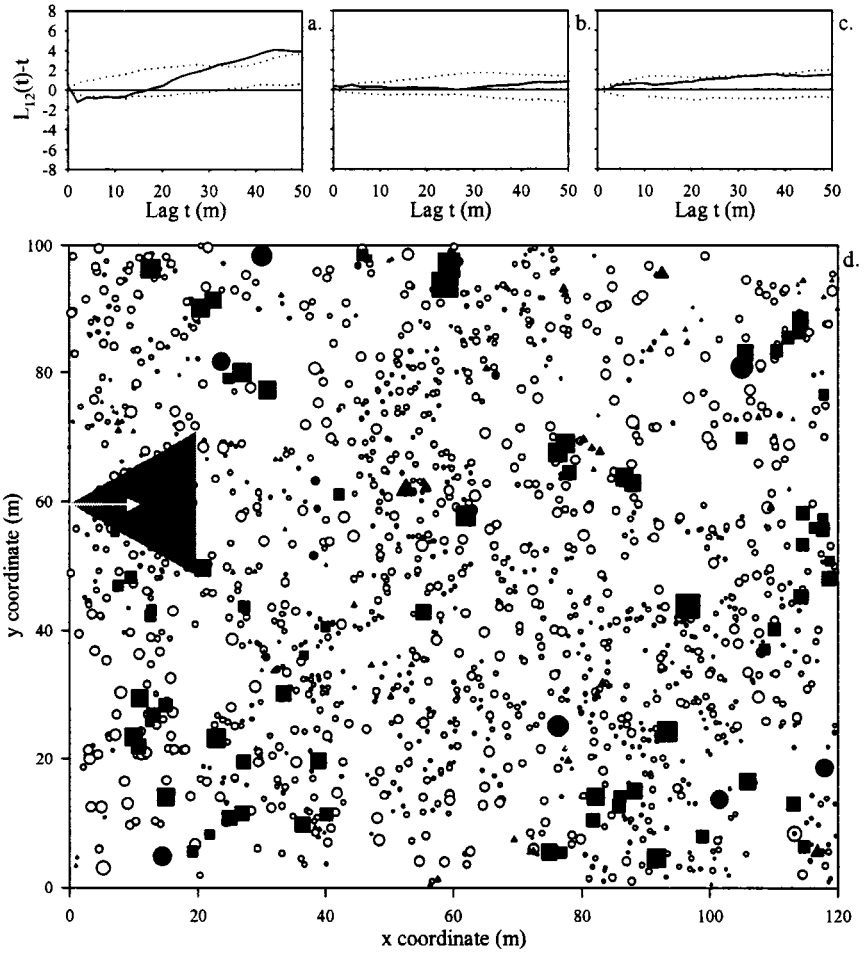

Figure 5.5. Ripley's $K_{12}(t)$ bivariate statistic, transformed as $[L_{12}(t)-t]$ as a function of lag distance(bottom) for live trees $\geq$ 9.14 cm DBH on S5B2 comparing spatial patterns of (a) pine trees, (b) pine stumps, and (c) oak trees present after 1913 Seed Tree harvest to the contemporary pine recruitment. The stem map (d) illustrates the locations of the pine recruitment (open circles), residual pine stems (closed circles) and stumps (closed squares), as well as the oak stems (closed triangles). Point size is proportional to stem diameter and on a different scale from tree coordinates for visual clarity. Arrow denotes repeat photo point location and shaded area denotes field of view.

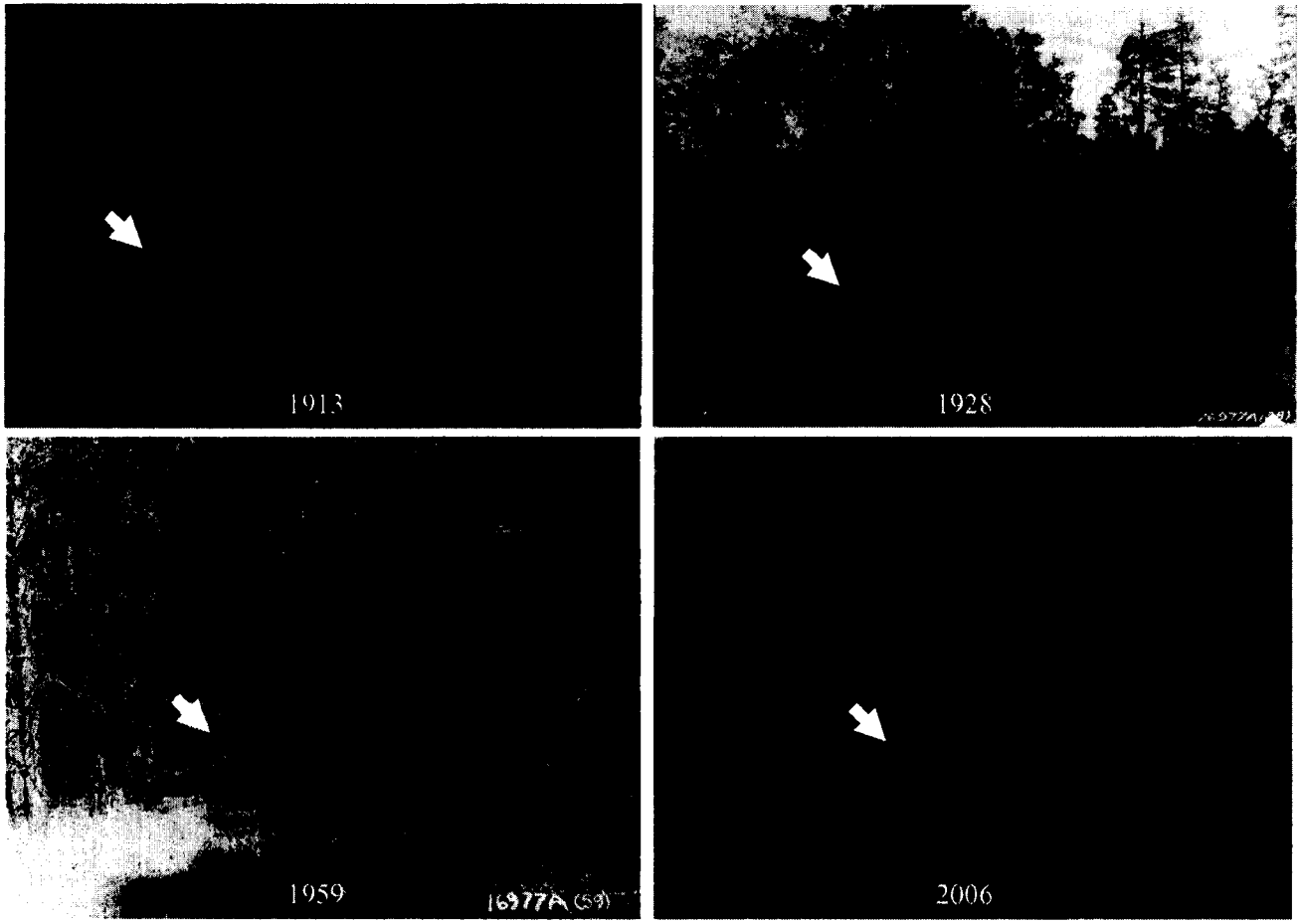

Figure 5.6. 1913 (top left), 1928 (top right), 1959 (bottom left), and 2006 (bottom right) photographs taken on S5B2 (Seed Tree System). Repeat photo point location shown in Fig. 5.5. The 1913 and 1928 photos were taken by H. Krauch (US Forest Service photo 16977A), the 1959 photo by M.M. Larson (US Forest Service photo LA-116), and the 2006 photo by A.J. Sánchez Meador. Plot excluded from grazing in 1919. Note dense patch of seedlings (1919 cohort) near stumps and high numbers of subsequent recruitment (1959, 2006).

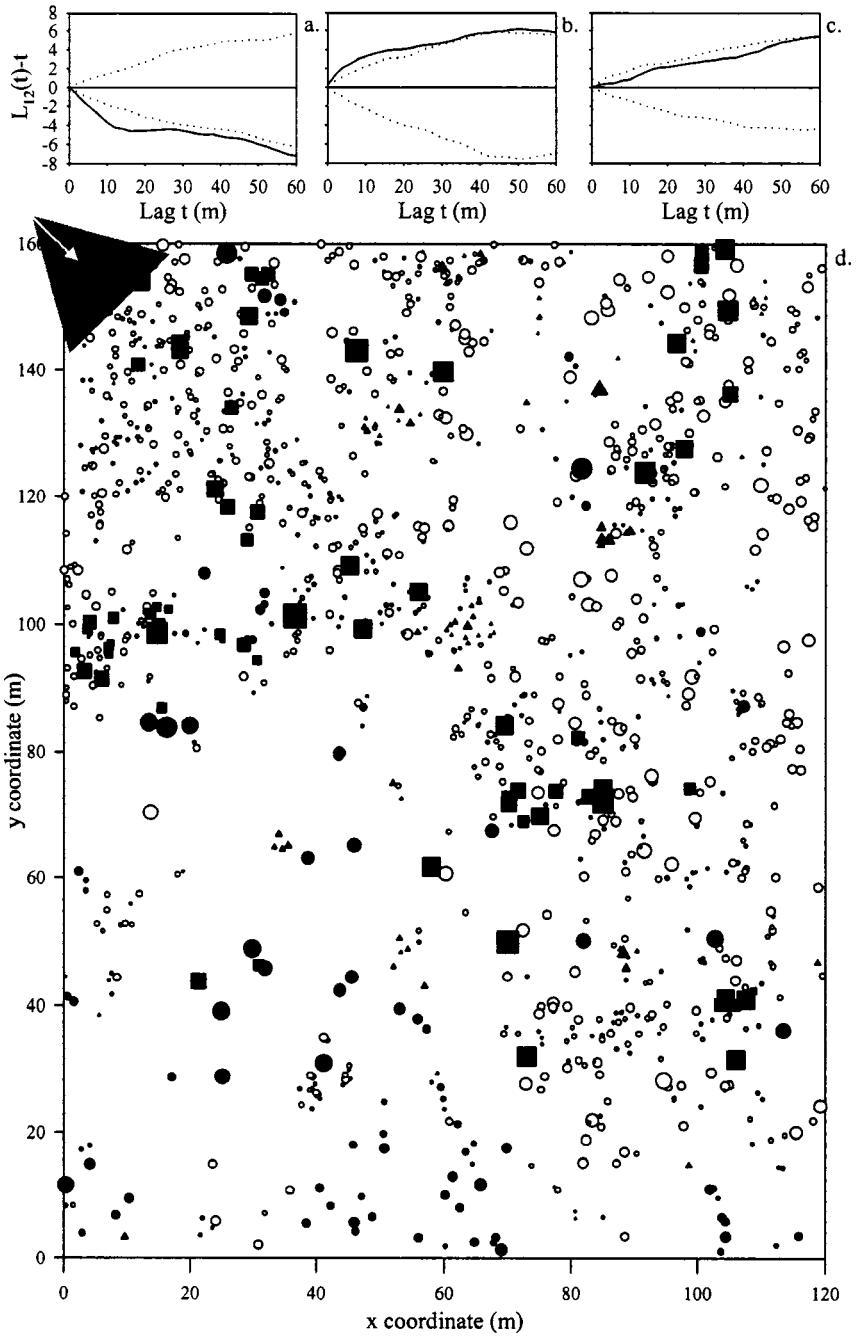

Figure 5.7. Ripley's $K_{12}(t)$ bivariate statistic, transformed as $[L_{12}(t)-t]$) as a function of lag distance(bottom) for live trees $\geq$ 9.14 cm DBH on S5B1 comparing spatial patterns of (a) pine trees, (b) pine stumps, and (c) oak trees present after 1913 Group Selection harvest to the contemporary pine recruitment. The stem map (d) illustrates the locations of the pine recruitment (open circles), residual pine stems (closed circles) and stumps (closed squares), as well as the oak stems (closed triangles). Point size is proportional to stem diameter and on a different scale from tree coordinates for visual clarity. Arrow denotes repeat photo point location and shaded area denotes field of view.

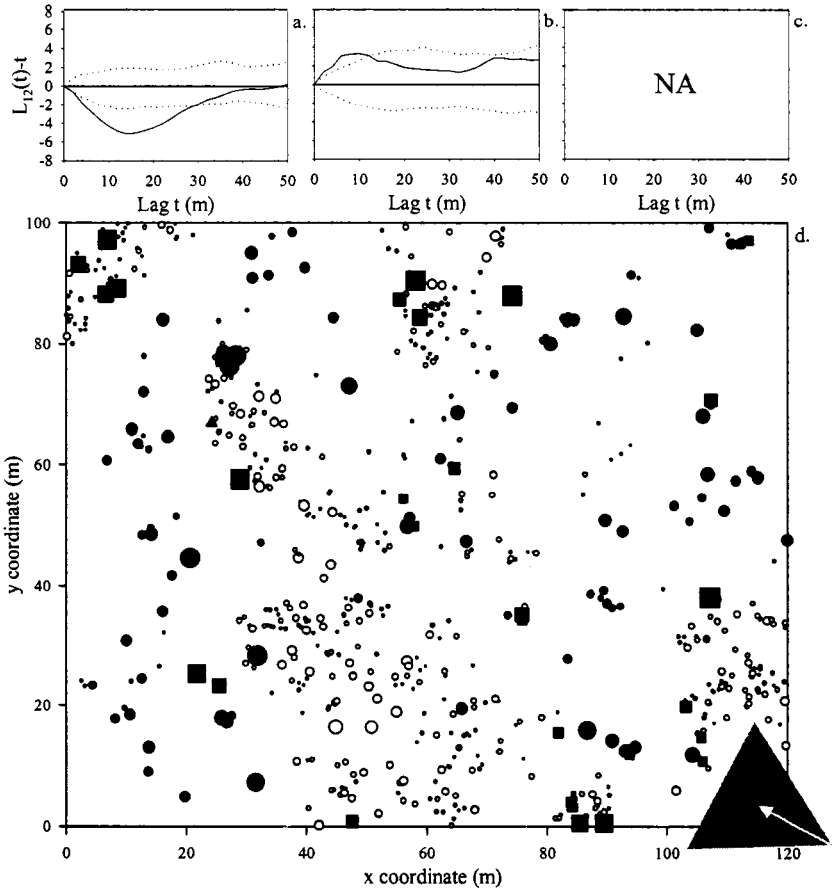

Figure 5.8. Ripley's $K_{12}(t)$ bivariate statistic, transformed as $[L_{12}(t)-t]$) as a function of lag distance(bottom) for live trees $\geq$ 9.14 cm DBH on S5B3 comparing spatial patterns of (a) pine trees, (b) pine stumps, and (c) oak trees present after 1913 Light Selection harvest to the contemporary pine recruitment. The stem map (d) illustrates the locations of the pine recruitment (open circles), residual pine stems (closed circles) and stumps (closed squares), as well as the oak stems (closed triangles). Point size is proportional to stem diameter and on a different scale from tree coordinates for visual clarity. Arrow denotes repeat photo point location and shaded area denotes field of view.

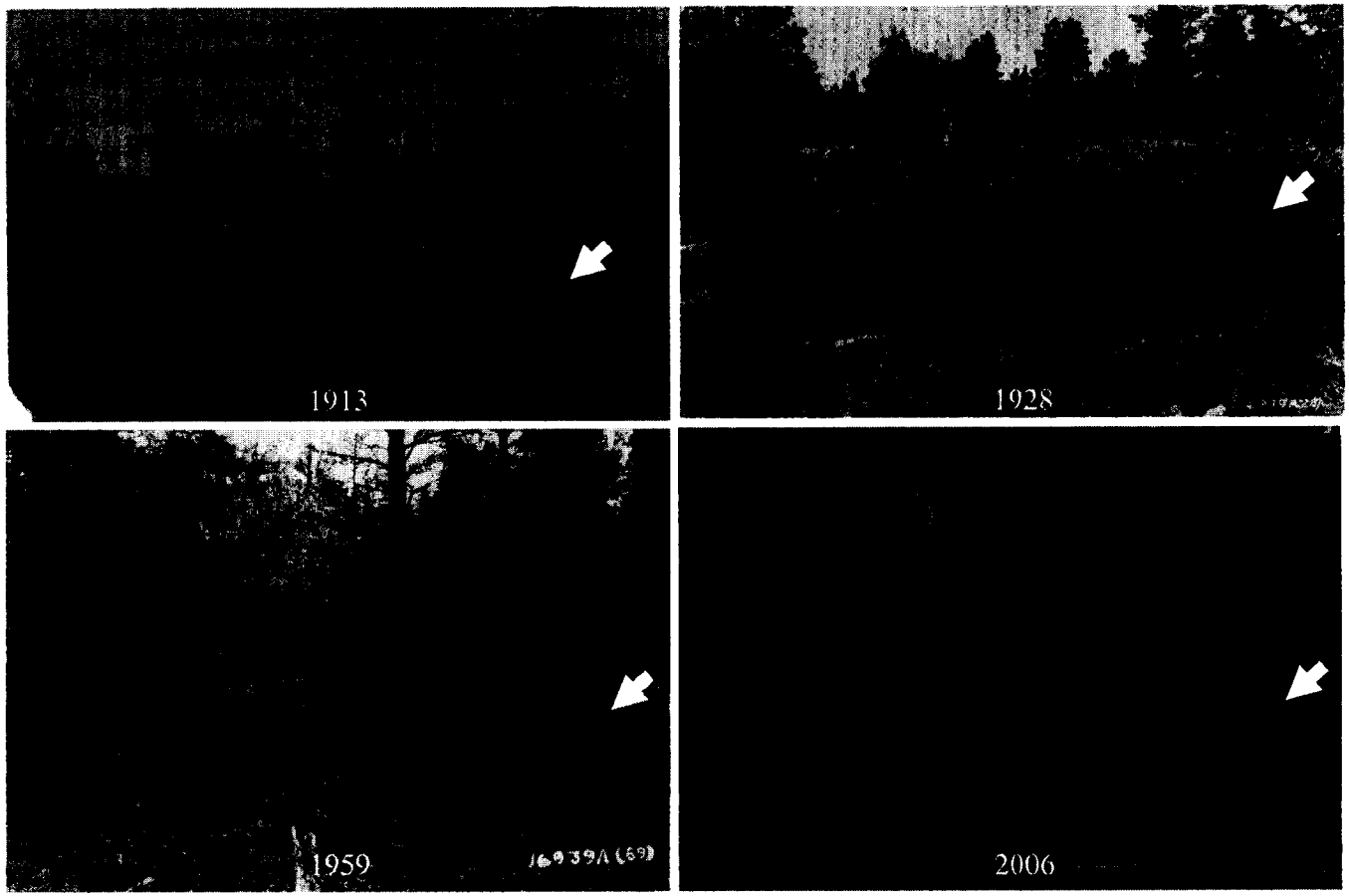

Figure 5.9. 1913 (top left), 1928 (top right), 1959 (bottom left), and 2006 (bottom right) photographs taken on S5B1 (Group Selection System). Repeat photo point location shown in Fig. 5.7. The 1913 and 1928 photos were taken by H. Krauch (US Forest Service photo 16939A), the 1959 photo by M.M. Larson (US Forest Service photo LA-87), and the 2006 photo by A.J. Sánchez Meador. Plot excluded from grazing in 1919. Note recruitment (1918 cohort) near pine stumps.

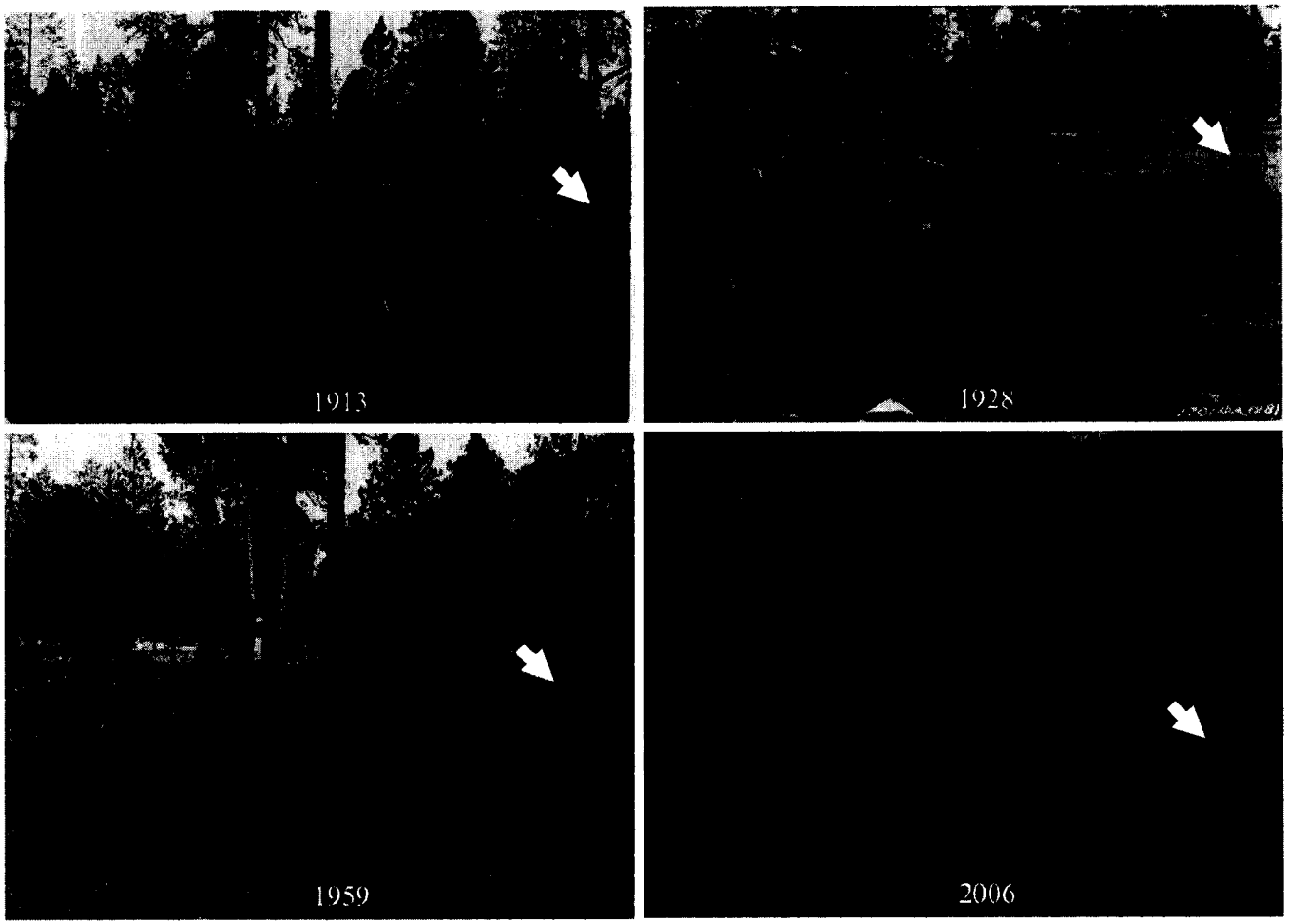

Figure 5.10. 1913 (top left), 1928 (top right), 1959 (bottom left), and 2006 (bottom right) photographs taken on S5B3 (Light Selection Method). Repeat photo point location shown in Fig. 5.8. The 1913 and 1928 photos were taken by H. Krauch (US Forest Service photo 17014A), the 1959 photo by M.M. Larson (US Forest Service photo LA-137), and the 2006 photo by A.J. Sánchez Meador. Plot excluded from grazing in 1919. Note openness of stand and recruitment near stump and downed log.

Chapter 6

Future Research Needs

The research conducted in this dissertation answered a limited set of research questions, and during this process, uncovered additional questions beyond the scope of this project's objectives. Unanswered questions related to spatial patterns reconstruction modeling are discussed in this chapter. Future studies addressing these questions would provide new information for land managers and would improve our understanding of spatial and temporal patterns in the southwestern ponderosa pine of north-central Arizona. Furthermore, these studies could better isolate linkages between stand conditions, anthropogenic and natural disturbances regimes, ingrowth and mortality, establishment patterns, and increase understanding of ecosystem processes.

Spatial Pattern Questions

Q1: Do the historical and contemporary spatial patterns observed on basalt-derived ponderosa pine sites persist over different spatial extents? It is well known that observation scales can influence ecological inference (Wiens 1989, Fortin and Dale 2005). The characteristics of a variable's distribution depend on the area or extent over which it is measured and if the size, shape, lag or extent of the analysis is changed, inference is mostly likely affected (Dungan et al. 2002). The effect of changes in size, shape, lag and/or extent on the measurement of tree spatial patterns and associations

between pine recruitment and the other antecedent populations sampled (i.e., residual stand following harvesting, stumps resulting from harvesting, and the grass openings) should be explored further. For example, examining effects of a change in extent could be accomplished by collecting a complete set of the locations of these populations on a historical plot several times larger than previously sampled (e.g., 4 ha). The stem-maps of progressively smaller extents (3, 2, 1-ha increments) would be complete subsets of the larger extent, thus facilitating observations of the degree of spatial association and inferences about change in underlying processes as affected by extent.

Observational studies to examine the effects of scale (expressed as size, shape, lag and/or extent) could be conducted on any large Woolsey plot (e.g., S4A, S1B, S3A which are 3.23, 4.04, and 4.85 ha in size, respectively) or within those areas historically sampled at the Gus Pearson Natural Area (e.g., White 1985, Biondi et al. 1994). For example, S1B (Chapters 3 and 4) could be sampled and the examination of spatial association patterns at multiple scales could help managers and researchers determine processes driving recruitment.

Q2: Do the contemporary spatial patterns in ponderosa pine sites of north-central Arizona on sedimentary-derived soils (limestone and sandstone) differ from those found on volcanic-derived soils (basalt)? Areas derived from basalt formations cover about half of the area in the Southwest forested by ponderosa pine, yet limestone and sandstone ponderosa pine sites are common (Schubert 1974). Numerous studies have examined the differences between sedimentary- and volcanic-derived soils, showing differences in post-fire mortality (Sackett et al. 1996) and soil nutrients (Neary et al. 2002), water yield (Solomon et al. 1975), and herbage production (Clary et al. 1968). Given this

information, combined with the varying results of spatial analyses conducted in ponderosa pine forests of the Grand Canyon National Park (Mast and Wolf 2004), the Colorado Front Range (Mast and Veblen 1999, Boyden et al. 2005), north-central Oregon and north-eastern California (Youngblood et al. 2005), and those in north-central Arizona conducted by Cooper (1961) and White (1985), I would expect the spatial patterns to differ.

Spatial analyses should be conducted on sites with similar overstory structure (primarily age and size distributions) and stand histories, but of soils differing in parent material, to determine if tree spatial patterns and corresponding pine recruitment patterns differ. Sites might include the Gus Pearson Natural Area for the basalt-derived soil type, Long Valley Experimental Forest for the limestone-derived soil type, and the Heber study area used by Ffolliott and Baker (1977) sandstone-derived soil type. Information on spatial pattern differences associated with parent material could help land managers determine suitable spatial scales to implement treatments and suitable spatial arrangements of fuel reductions treatments (i.e., patchy vs. regular spacing).

Q3: How do spatial patterns following different silvicultural prescriptions compare to those observed prior to Euro-American settlement? Forested stands are manipulated to achieve a range of management objectives through various silvicultural treatments. These treatments affect the spatial pattern of individual trees and greatly affect observed stand dynamics and ecosystem processes (Chapter 2 and 5). Various research methods might be used to examine the effects of currently implemented silvicultural prescriptions on spatial patterns. One such study might include thinning comparable stands to variable densities, each with a different spatial pattern. The

resulting changes in tree growth, regeneration patterns, and resource availability should be quantified and compared to reconstructed presettlement structure (e.g., Chapter 3 and 4). This research could identify prescriptions and/or silvicultural methods that are most sensitive to patch-, stand-, and watershed-level spatial patterns and would provide insights into the effects of spatial pattern on understory production, wildlife habitat, and wood quality.

Modeling Improvements and Opportunities

In Chapter 3, I utilized six historically stem-mapped, permanent plots established in the early 20th century, to develop a reconstruction model and provide reference conditions for ponderosa pine structure of north-central Arizona prior to Euro-American settlement. This unique data set contained detailed information on the location and sizes of live trees, stumps, snags, and logs at dates 30 after fire exclusion. During the development of this model, I noted shortcomings in the methods used to predict the previous growth of live trees and the decomposition of dead trees. While there are numerous methods available to model tree growth (Peng 1999) and decomposition (Thomas et al. 1979, Cline et al. 1980, Raphael and White 1984, Kruys et al. 2002, Harmon et al. 2003) in uneven-aged forests, few methods have been applied to reconstruct past forest structures. Two potential studies addressing the application of current modeling techniques to ponderosa pine reconstruction follow:

Q4: Would individual-tree models utilizing competition indices more accurately model previous basal area growth, and therefore improve dendrochronological reconstructions of reference conditions? Current reconstruction models used in

determining reference conditions utilize growth estimates based on site-specific predictive regression relationships, often between diameter and previous basal area increment (Fulé et al. 1997, Fulé et al. 2002). These relationships are often weak. The lack of an adequate model to simulate and predict previous growth in spatially aggregated, uneven-aged stands of ponderosa pine led me to consider alternative approaches. A distance-dependent modeling approach that uses competition indices is an obvious choice for examination, based on the fact these approaches have been applied with success in uneven-aged stands (e.g., Pukkala et al. 1987, Radtke et al. 2003).

Distance-dependent competition indices have been widely used and tested in the past, but the indices proposed by Lorimer (1983), Hegyi (1974), and Larson (1968) might be the best choice with the Woolsey data. Woolsey data could be used to validate the models given different management regimes and soils, while historical data from the Gus Pearson Natural Area could be used to asses model performance in minimally disturbed conditions.

Q5: Are snag and woody debris dynamics more accurately modeled using a Markov chain matrix model and could their application improve dendrochronological reconstructions of reference conditions? Large woody debris like snags and downed logs are known to be of considerable importance for wildlife habitat (Maser et al. 1979, Laudenslayer 1997, Bate et al. 1999, Payer and Harrison 2002, Lehmkuhl et al. 2003), nutrient cycling and carbon dynamics in forest ecosystems (Maser and Trappe 1984, Harmon et al. 1986, Hart 1993), and for their influence on fire behavior and insect outbreaks (Maser et al. 1979, Spies et al. 1988, Covington and Moore 1994a, 1994b). Tree decomposition research and modeling examining snag and downed log dynamics

often use classification systems to describe the succession from a newly killed tree to a completely decomposed log (e.g., Fogel et al. 1973), but often inaccurately assume linear progression through classes. While these linear, stage-based, classification systems enable a description of the decay process without time-consuming measurements of current wood density, estimates of initial density, and tree-ring measurements; they do not account for the often non-linearity of tree decomposition.

An area showing promise for the modeling of non-linear dead tree dynamics and transition rates between different decomposition classes is Markov chain matrix modeling (sensu Caswell 2001). Markov chains are commonly used to model dynamics in a variety of settings, including forest succession (Waggoner and Stephens 1970, Horn 1975, Runkle 1981), plant community dynamics (Isagi and Nakagoshi 1990), insect assemblages (Usher 1979), and forest growth-and-yield (Bruner and Moser 1973, Cassell and Moser 1974, Frazier 1978). A Markov chain matrix model applied backward (Solow and Smith 2006) to model individual dead tree transition rates between decay classes and thus form a stage-based matrix model might be more effective is modeling decomposition. The model could be parameterized and /or validated with data from the permanent historical plots used by Moore et al. (2004) or using data from the nearby Gus Pearson Natural Area.

Conclusion

The research presented in this dissertation answered several questions related to the spatial patterns for southwestern ponderosa pine forests of north-central Arizona and provided reconstruction reference conditions for this forest type. Several new questions were generated from this research, most of which could be addressed using observational

and/or modeling studies. Answers to these questions would increase our basic understanding of forest structure and provide insights into processes important in ponderosa pine ecosystems and consequences of past and future management practices. Furthermore, information gathered in these studies would help land managers make decisions that are more informed and assist in the evaluation of techniques designed to restore ecological integrity to forests in this system.

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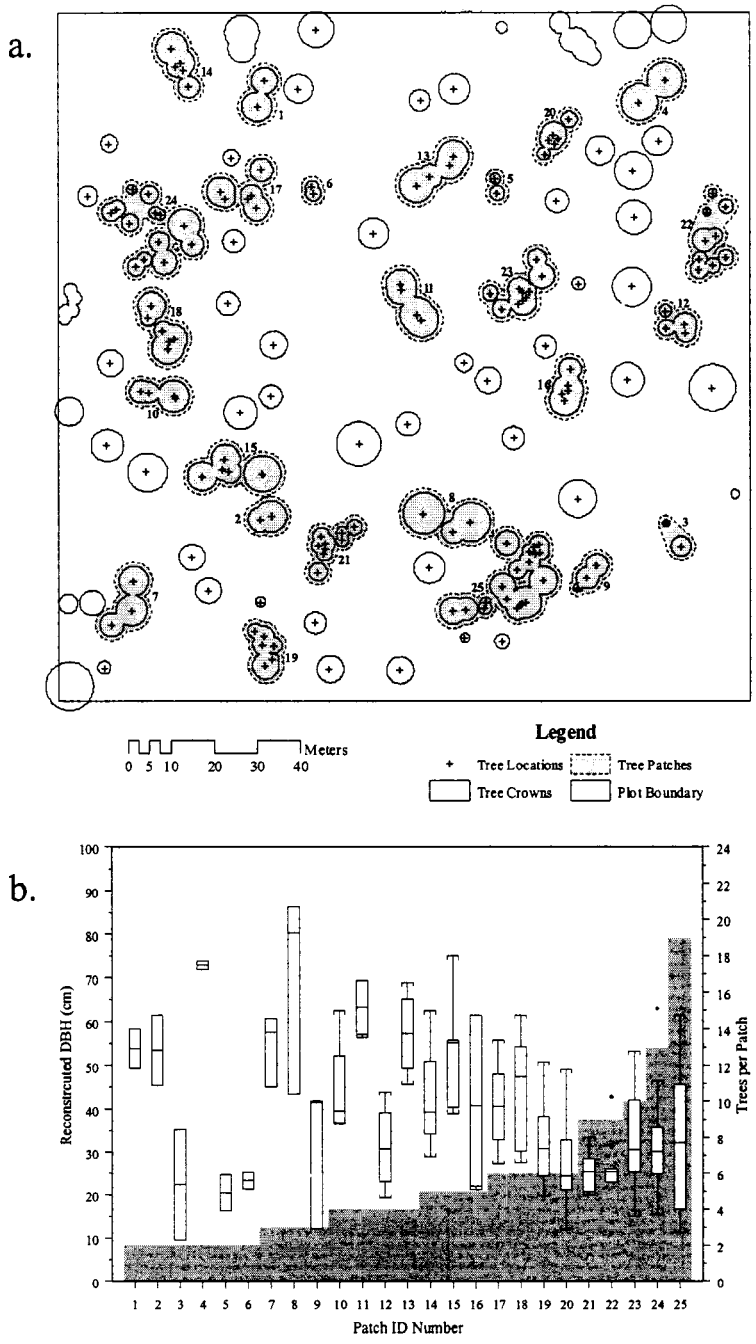
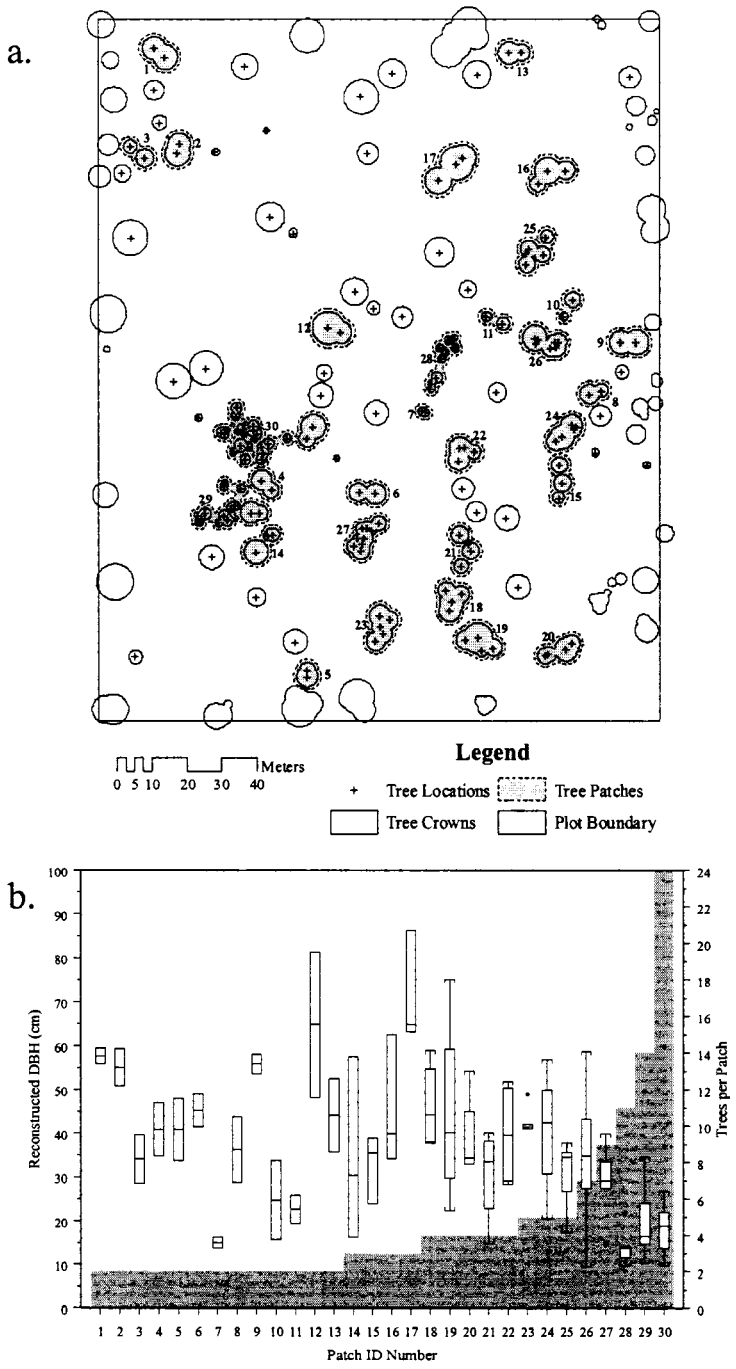
Appendix

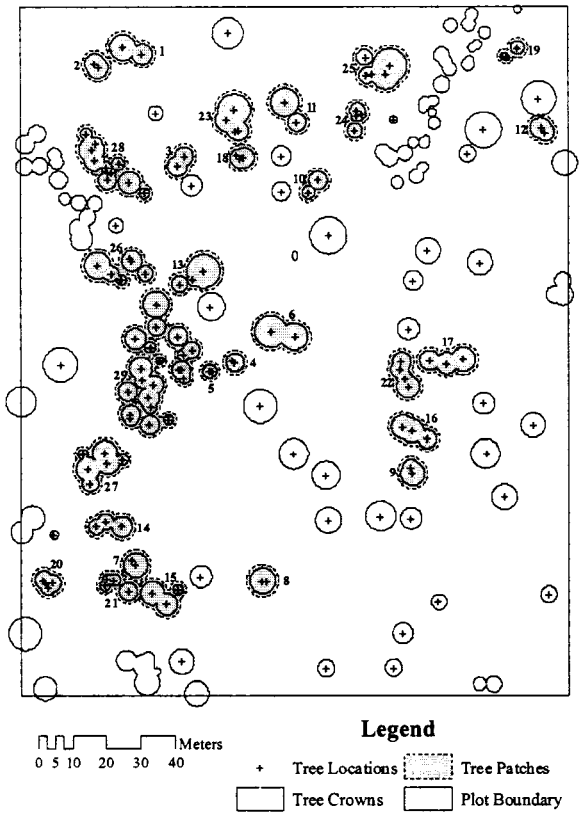


Appendix 4.7. (a) Reconstructed stem-maps for COCS1A prior to Euro-American settlement (1874) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.



Appendix 4.8. (a) Reconstructed stem-maps for COCS4A prior to Euro-American settlement (1874) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.

a.



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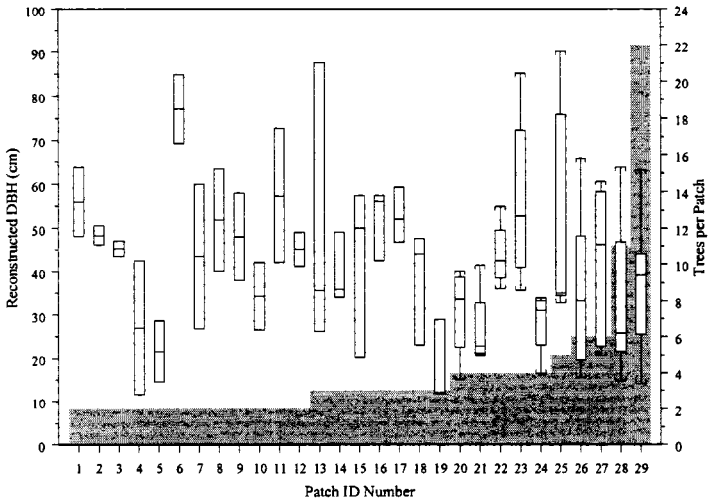
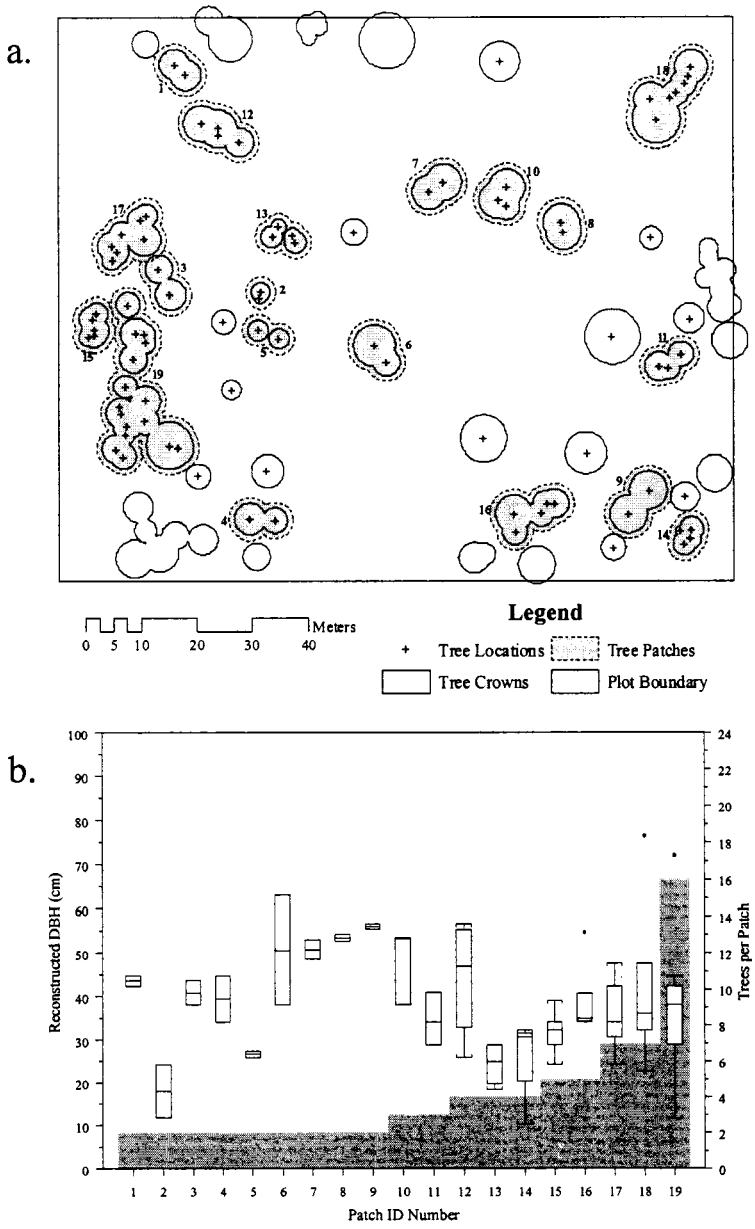


Appendix 4.9. (a) Reconstructed stem-maps for COCS4B prior to Euro-American settlement (1874) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.



Appendix 4.10. (a) Reconstructed stem-maps for COCS5B2 prior to Euro-American settlement (1873) showing the location of live trees (DBH $\geq$ 9.14 cm), projected tree canopies, and distinct tree patches (with ID number) and (b) corresponding box plots illustrating reconstructed diameter distribution for live trees in patches (arranged by increasing patch density) and corresponding patch density (shaded area) on second y-axis.

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